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NOAA Ship Okeanos Explorer EX-21-01 EM 304 MKII Sea Acceptance Testing Report

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Table of Contents

Introduction

NOAA Ocean Exploration is the only federal program dedicated to exploring the deep ocean, closing prominent gaps in our basic understanding of U.S. deep waters and the seafloor and delivering the ocean information needed to strengthen the economy, health, and security of our nation.

Using the latest tools and technology, the office explores previously unknown areas of our deep ocean, making discoveries of scientific, economic, and cultural value. Through live video streams, online coverage, training opportunities, and real-time events, NOAA Ocean Exploration allows scientists, resource managers, students, members of the general public, and others to actively experience ocean exploration, expanding available expertise, cultivating the next generation of ocean explorers, and engaging the public in exploration activities. To better understand our ocean, the office makes exploration data available to the public. This allows us, collectively, to more effectively maintain ocean health, sustainably manage our marine resources, accelerate our national economy, and build a better appreciation of the value and importance of the ocean in our everyday lives.

Report Purpose and Executive Summary

The purpose of this report is to describe the sea acceptance testing (SAT) of the Kongsberg EM 304 MKII multibeam echosounder transmit (TX) array that replaced the original Kongsberg EM 302 TX array during the 2020-2021 winter maintenance period. The TX cards in the EM 304 topside unit that was replaced in 2020 were upgraded to the MKII variant, and the Seafloor Information System (SIS) acquisition software was updated to version 5.6.0. The TX array modules are serial numbers 1-14, signifying an early adoption of the MKII following the extended service life of the original EM 302 TX modules. No changes were made to the receive (RX) array, which was replaced in 2018.

The POS MV GNSS antennas were upgraded to Trimble GA830 units to improve the rejection of interference from transmitters, such as the Iridium. Software and firmware upgrades were applied to the Applanix POS MV positioning and attitude system.

A complete survey of the vessel was conducted by Westlake Consultants while the ship was in dry dock, including the placement of welded benchmarks throughout the ship. The granite block remains the origin for all mapping sensor configurations. Linear and angular offsets for the POS MV Inertial Measurement Unit (IMU), EM 304 arrays, and the GNSS antennas were provided following the National Science Foundation (NSF) funded Multibeam Advisory Committee (MAC) recommendations.

The Westlake survey is believed to be of very high quality; the POS MV GNSS Azimuth Measurement Subsystem (GAMS) antenna baseline calibration converged quickly in agreement with the surveyed baseline, and the angular offsets determined by the EM 304 geometric calibration (‘patch test’) are small. Swath artifacts that are occasionally attributable to lower accuracy surveys due to potential error in transducer array angles were not apparent in the EX-21-01 data, despite the high sound speed variability observed in the operational areas.

Sea acceptance testing (SAT) for the new MKII TX array was conducted during EX-21-01, primarily between April 16-22, 2021 in the Gulf of Mexico, with additional data collection occurring through May 10, 2021. Kongsberg, NOAA Ocean Exploration, and NOAA Office of Marine and Aviation Operations (OMAO) personnel on board collaborated to complete the following procedures:

- Reviewing the Westlake report and EM 304 / POS MV system geometry.
- Configuring the EM 304 with the installation parameters derived from the 2021 vessel survey conducted by Westlake Consultants.
- Completing POS MV GAMS calibrations to verify the surveyed antenna baseline.
- Calibrating the EM 304 for residual angular offsets attributable to sensor installation angles.
- Assessing EM 304 accuracy across all depth modes using 250 m, 1,100 m, 3,400 m, and 5,200 m reference sites. The 3,400 m reference survey also satisfied the demonstration survey required under the Kongsberg SAT contract.
- Evaluating swath coverage achieved by the system over a wide range of depths and documenting unexpected behavior.
- Estimating data rates from EM 304 .kmall and .kmwcd files, and comparing these rates to EM 302 .all and .wcd examples from EX-19-02.
- Examining RX noise levels perceived by the EM 304 over a wide range of speeds.
- Collecting backscatter normalization datasets across Shallow through Very Deep modes at two sites, contributing to the establishment of a reference area for other vessels operating within this region.
- Assessing EM 304 performance and software functionality with Kongsberg engineering support.

The geometric calibrations were completed at a site near Key West, Florida. The angular offsets were determined to be small, reflecting a high-quality vessel survey and suggesting correct offset implementation within EM 304 and POS MV software. These results confirm the successful integration of the EM 304 MKII.

A very slight potential roll bias of less than 0.01° was observed intermittently during certain survey lines and accuracy tests. Crosslines conducted at the 1,100 and 3,400 m accuracy sites were used for roll verification, with results centered around zero throughout a wide range of subsets. No offset correction will be implemented unless additional survey data indicates the presence of a more consistent roll bias.

Accuracy testing indicated expected performance across all modes. A SIS configuration error in the application of attitude velocity input was discovered after it quietly disabled FM during the 3,400 m accuracy test. The configuration was corrected and additional accuracy crosslines were conducted with FM fully enabled and utilized.

Swath coverage achieved during EX-21-01 generally met expectations, with a coverage increase of approximately 0.25 to 1 times the water depth in depths ranging from 1,500-3,500 m when compared to EX-18-10 and EX-19-02 data. This improvement in deep water coverage is a result of redesigning the system to perform better in deep water, but has a negative effect of coverage decrease in shallow waters due to a reduction in the maximum angle from 75°/75° (EM 302) to 70°/70° (EM 304). An unexpected delay in automatic switching from Deeper to Very Deep is being investigated by Kongsberg with input from the NOAA Ocean Exploration mapping team and EX-21-01 coverage trends.

Noise levels perceived by the EM 304 MKII over a range of speeds showed trends similar to the 2020 EM 304 MKI results. The MKII hardware upgrade did not include RX hardware, however the 2021 data showed a slightly elevated noise floor when compared to 2020 data. This is possibly related to a higher susceptibility to lower frequency propulsion noise in the broader EM 304 MKII frequency range. These results do not seem to materially impact routine mapping operations.

TX and RX channel built-in system test (BIST) data collected at the start of EX-21-01 provide a proxy for baseline hardware health at the start of the MKII service life, with only two of the 1,002 TX elements and one RX element out of factory specification.

Qualitatively, the seabed imagery produced in real-time by the EM 304 looked fairly consistent. Ideally, Kongsberg will be able to process the backscatter normalization data collected during EX-21-01 quickly, and corrections can be applied to data collected throughout the majority of the 2021 field season.

The POS MV experienced dropouts late in the Atlantic portion of the SAT, occurring at the same time of day for approximately 1 - 1.5 hours on two subsequent days. This resulted in erroneous or missed pings in the EM 304. Applanix has been contacted and is working with the mapping team to address this and ensure reliable mapping operations.

The stability of the SIS software has significantly improved since the 2020 EM 304 SAT. The processing unit (PU) and SIS machines both still required nearly daily restarts to prevent some critical issues resulting in windows freezing and software crashes, however. These issues have been submitted to Kongsberg.

Onboard Personnel

Table 1. EX-21-01 onboard science party members involved with the EM 304 SAT.

Name	Role	Affiliation
Shannon Hoy	Expedition Coordinator	NOAA Ocean Exploration (CNSP)
Sam Candio	Expedition Coordinator (in training)	NOAA Ocean Exploration (CNSP)
Charlie Wilkins	Senior Survey Technician	NOAA OMAO
Kevin Jerram	Mapping Watch Lead	University Corporation for Atmospheric Research
Erin Heffron	Mapping Watch Lead	University Corporation for Atmospheric Research
Adam Hughes-Wooton	Engineering	Kongsberg
David Blessing	Chief Electronic Technician	NOAA OMAO
Andy Lister	Data/Network Team	Global Foundation for Ocean Exploration
Mark Durbin	Data/Network Team	Global Foundation for Ocean Exploration
Jim Meyers	Data/Network Team	Global Foundation for Ocean Exploration
Chris Wright	Data/Network Team	Global Foundation for Ocean Exploration

Primary SAT Activities

The primary SAT activities included:

- Update EM 304 and POS MV configurations based on the 2021 Westlake Consultants vessel survey, including a new waterline calculation.

- EM 304 dockside BISTs (including TX channels) for Harbor Acceptance Testing (HAT).
- POS MV GAMS calibration.
- Geometric calibration ("patch test").
- Accuracy testing at four depths to assess each mode:
  - 250 m: Shallow, Medium
  - 1,100 m: Deep, Deeper
  - 3,400 m: Deeper, Very Deep, Extra Deep, Extreme Deep
  - 5,200 m: Very Deep, Extra Deep, Extreme Deep
- RX noise vs. speed testing.
- Swath extinction data collection during transits.
- Training and troubleshooting with Kongsberg support.
- Integration testing with K-Sync and Sound Speed Manager.

Survey System Components

The primary mapping system components were:

- Kongsberg Maritime EM 304 MKII multibeam echosounder (20-32 kHz, 0.5° TX x 1.0° RX).
  - TX 1 s/n 117, TX 2 s/n 119, RX s/n 112, processing unit (PU) s/n 10016.
- Kongsberg Maritime Seafloor Information System.
  - SIS v5.6.0.441.
- Applanix POS MV-320 V5 navigation system.
  - Receiver s/n 5505C03528.
- Reson SVP-70 surface sound speed sensor (primary source for EM 304).
- Flow through thermosalinograph (TSG) for surface sound speed (secondary source for EM 304).
- Atlantic Oceanographic and Meteorological Laboratory (AOML) auto-launcher expendable bathythermograph (XBT) profiling system.
- Sippican manual XBT profiling system.
- Seabird SBE 9plus conductivity, temperature, depth (CTD) profiling systems.

EM 304 General Specifications

Table 2. Manufacturer specifications of the EM 304 MKII.

Measurements	Bathymetry/Seabed Image/Water Column Backscatter
Frequency	26 kHz (20 to 32 kHz)
Depth	10 to 11,000 m
TX Beams	Multisector (maximum 8 sectors per swath)/dual swath enabled

RX Beams	512 (800 soundings per swath in High Density Mode)
Beam Widths	0.5° TX/1.0° RX
Signal Shapes	CW/FM
Transmit Modes	Shallow: 10-250 m, 4 TX sectors per swath Medium: 250-750 m, 4 TX sectors per swath Deep: 750–1,000 m, 8 TX sectors per swath Deeper: 1,000–3,300 m, 8 TX sectors per swath Very Deep: 3,300–5,000 m, 6 TX sectors per swath Extra Deep: 5,000–7,000 m, 4 TX sectors per swath Extreme Deep: > 7,000 m, 2 TX sectors per swath

EM 304 MKII TX Features

Below is a review of the reported differences between the EM 304 MKI (with EM 302 TX array modules) and the EM 304 MKII TX array upgrade.

- Improved TX bandwidth and power with fewer cables and LPTX36 boards.
- Improved swath coverage.
- Roll stabilization increased from 10° to 15°.

System Geometry Review

Below is a review of the EM 304 and POS MV system geometry.

- The original EM 302 RX array was replaced in 2018, the original EM 302 transceiver unit (TRU) was upgraded to an EM 304 in 2020, and the original EM 302 TX array was replaced with an EM 304 MKII variant during the 2020-2021 winter maintenance period.
- The POS MV GNSS antennas were updated to Trimble GA830 units during the 2020-2021 winter maintenance period. The GA830s maintain the same locations on the bridge antenna mast as the previous antennas.
- The vessel and all EM 304 and POS MV components were surveyed by Westlake Consultants and reported according to the Kongsberg / Applanix conventions and MAC recommendations. The origin remains at the granite block, and the survey utilizes and reaffirms the long-standing mapping system reference frame on board.
    - Linear offsets are reported in meters in a “right handed system”, with positive X forward, positive Y starboard, and positive Z down.

- Angular offsets are reported in decimal degrees, with positive roll starboard side down, positive pitch bow up, and positive heading with bow rotation to starboard.
- The EM 304 was configured prior to EX-21-01 SAT data collection using all Westlake reported offsets, zeroing out Attitude 1 in SIS. Patch test results were applied in Attitude 1 and were small, reflecting a high quality survey.

POS MV Configuration

The POS MV lever arms and angles were updated with the Westlake results prior to EX-21-01, with the GNSS antenna heights set to the L1 phase center heights calculated by Westlake using the Trimble GA830 antenna drawings.

Four GAMS calibration iterations were conducted on April 16, 2021, prior to the EM 304 calibration. Each individual GAMS baseline result varied up to approximately 1 cm in the alongship and vertical directions between tests. The average GAMS baseline fell within 0.001 m in the athwartship and vertical directions, and within 0.006 m in the alongship direction from the surveyed baseline. The antenna baseline results from each test confirmed the surveyed antenna baseline, which was left unchanged in POSView.

EM 304 Lever Arms and Angles

The granite block remains the origin for all sensor reference frames, with all angles reported relative to the vessel horizontal and vertical planes per Kongsberg and Applanix conventions. At the start of EX-21-01, the EM 304 installation parameters were configured using the 2020/2021 Westlake Consultant vessel survey offsets.

Attitude 1 (POS MV IMU) angular offsets in SIS were set to zero prior to the geometric calibration, and subsequently updated with the results of the calibration. Attitude 2 (attitude velocity for FM Doppler correction) installation angles were set to zero; it is not expected that these angles have any impact on calibration results.

Waterline Calculation

The waterline within the EM 304 reference frame was determined through measuring sea surface heights with a weighted draft measuring tape at three pairs of the 2” by 2” welded benchmarks identified in the Westlake Report while dockside on April 14, 2021. The benchmarks selected were 850 and 851 on the bow, 603 and 669 at midship, and 604 and 619 on the stern. Waterline (Z) estimates and alongship (X) estimates were averaged for each pair of benchmarks to estimate the waterline at the centerline for the three alongship areas. A linear fit of the three averages provided an estimate of +1.80 m at the origin alongship location, rounded to acknowledge uncertainty in the measurements (**Figure 1**).

Through the waterline calculation process and discussions with the port engineer, it is believed that the draft marks on the bow are referenced to the original keel rather than the transducer blister. This discrepancy may explain the approximately 0.40 m difference between the historic SIS waterline value of +2.20 m and the new value of +1.80 m that has been updated in SIS.

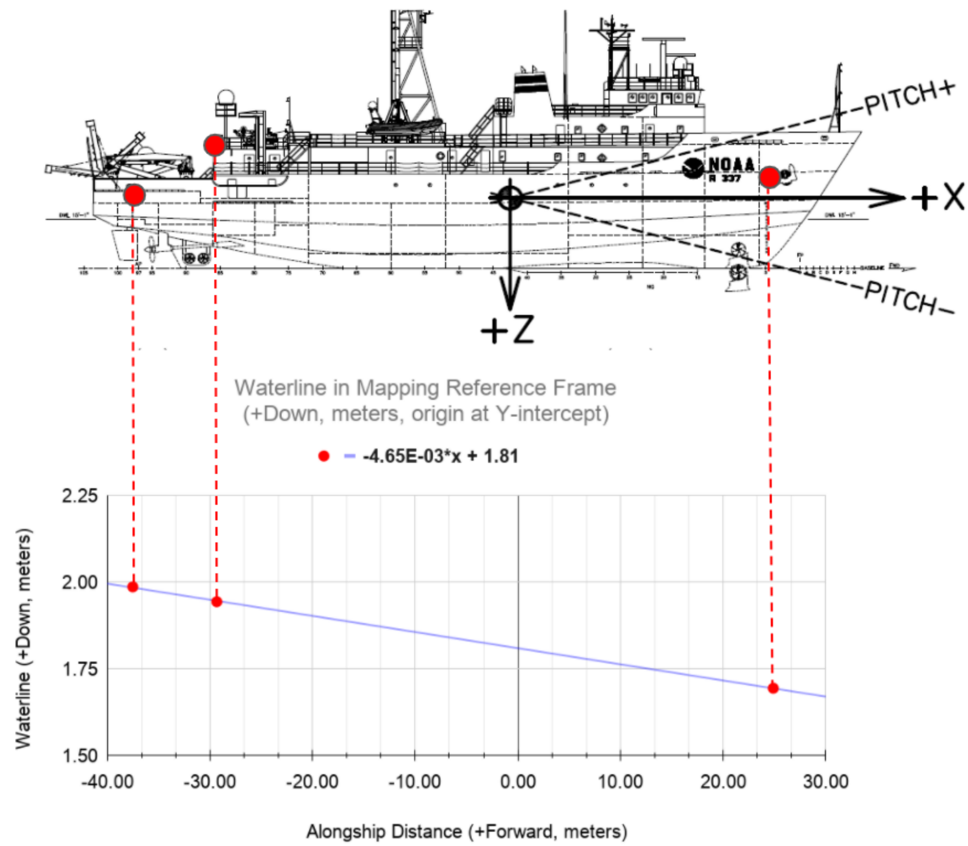

Figure 1. EX-21-01 waterline calculation.

EM 304 Calibration Site Selection and Data Collection

A calibration plan was developed for EX-21-01 at a site on the Florida Escarpment with suitable slopes and bathymetric relief (**Figure 2**). This region was selected to minimize the transit distance from Key West en route to deeper water for coverage and accuracy testing. Calibration lines were run at 6 knots in the following order:

1. Pitch (A to B and B to A)

2. Roll (C to D and D to C)
3. Heading (E to F and G to H)

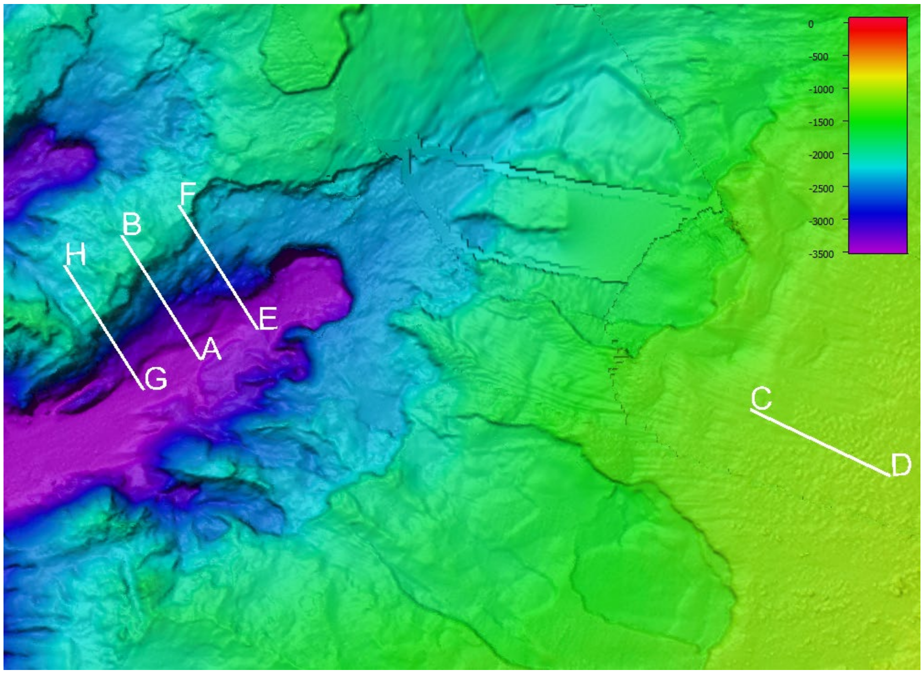

Figure 2. EX-21-01 calibration site and line plan (depths in meters).

No dedicated verification lines were conducted, as the initial calibration data indicated very clear results. Roll verification was conducted using accuracy survey crosslines in depths of 1,100 m and 3,400 m.

XBT casts were conducted prior to the first pitch line and first roll line. All sound speed profiles were processed in Sound Speed Manager using World Ocean Atlas 2013 salinity data and applied in SIS during data collection. Post-processed sound speed data were applied on a “nearest in time” basis. A CTD cast was taken at this site, and is available for post processing if deemed necessary.

SIS installation parameters for Attitude 1 were set to zero prior to the EX-21-01 calibration. Calibration data were examined with the patch test tool in QPS Qimera between each test in order to apply the results in SIS prior to each subsequent test. Calibration processing within SIS was not possible during the test due to a software issue.

The results of each test indicated small adjustments that were subsequently applied in SIS. The final offsets applied were -0.02° for pitch, 0.00 for roll, and +0.15° for heading. Iterative testing in Qimera indicated no further adjustments were necessary beyond the initial results. Positioning latency was checked through a comparison of the second pitch line with a high-speed return transit on the same course in between heading lines, ensuring that consistent pitch values were applied to both lines in the Qimera vessel configuration. This type of latency test is normally inconclusive in deep water, and no position or attitude latencies were readily apparent in the bathymetry.

EM 304 Swath Coverage

During transits throughout EX-21-01, the EM 304 was run in automatic ping mode with swath angle limits of ±70° to let the system select the most appropriate mode for particular water depths and attempt to maximize swath coverage. Calibration and accuracy testing required various swath angle reductions; these data have been omitted from the swath coverage analysis. Additionally, files inadvertently collected with FM disabled prior to resolving an attitude velocity issue in SIS have been excluded from the coverage assessment.

The outermost port and starboard valid soundings for all pings were plotted using MAC/NOAA tools to evaluate trends in the achieved swath width versus depth (**Figure 3**). This coverage curve is useful for examining the improvements with the MKII upgrade, survey line planning, and setting a baseline for performance with the new TX array. Among other vessels, reductions in coverage have indicated increasing vessel noise or hardware issues such as reduced transmission strength. Note that transits were conducted at 9-10 knots rather than the typical survey speed of 8-9 knots; the speed, various sea states, and oblique transits across the Florida Escarpment and continental slope may negatively (or unevenly) impact swath coverage.

Additional coverage testing conducted near Blake Ridge was complicated by weather and unexpected mode-switching behavior.

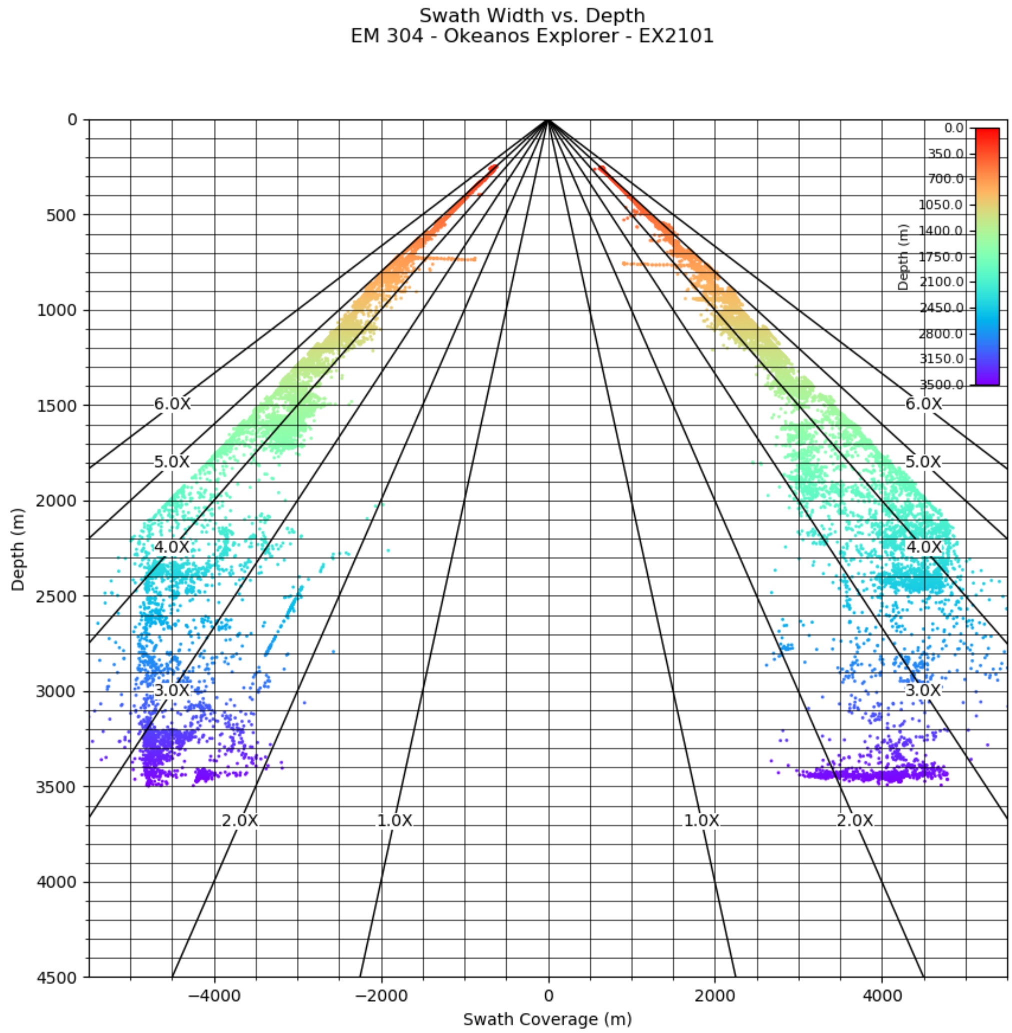

Figure 3. Plot of EM 304 swath width as a function of depth (in meters).

EX-21-01 extinction data show generally symmetric coverage, and suggest no systemic coverage limitations resulting from hardware or vessel noise. The EM 304 generally achieved full coverage across the full 140° swath down to a depth of 500 m. The system then reported swath coverage of 4-5 times the water depth down to 1,500 m before beginning to show rapid roll-off due to acoustic attenuation at longer ranges. Throughout the expedition the EM 304 generally switched depth modes as expected to maximize swath width while in Auto mode in depths up to 3,500 m.

During the transit to the 5,200 m reference survey, the EM 304 continued to choose Deeper mode while in Auto in waters deeper than 4,400 m before being manually forced into Very Deep mode. This was well beyond the initial expected transition depth of 3,300 m, leading to reduced swath quality and coverage (**Figures 4 and 5**).

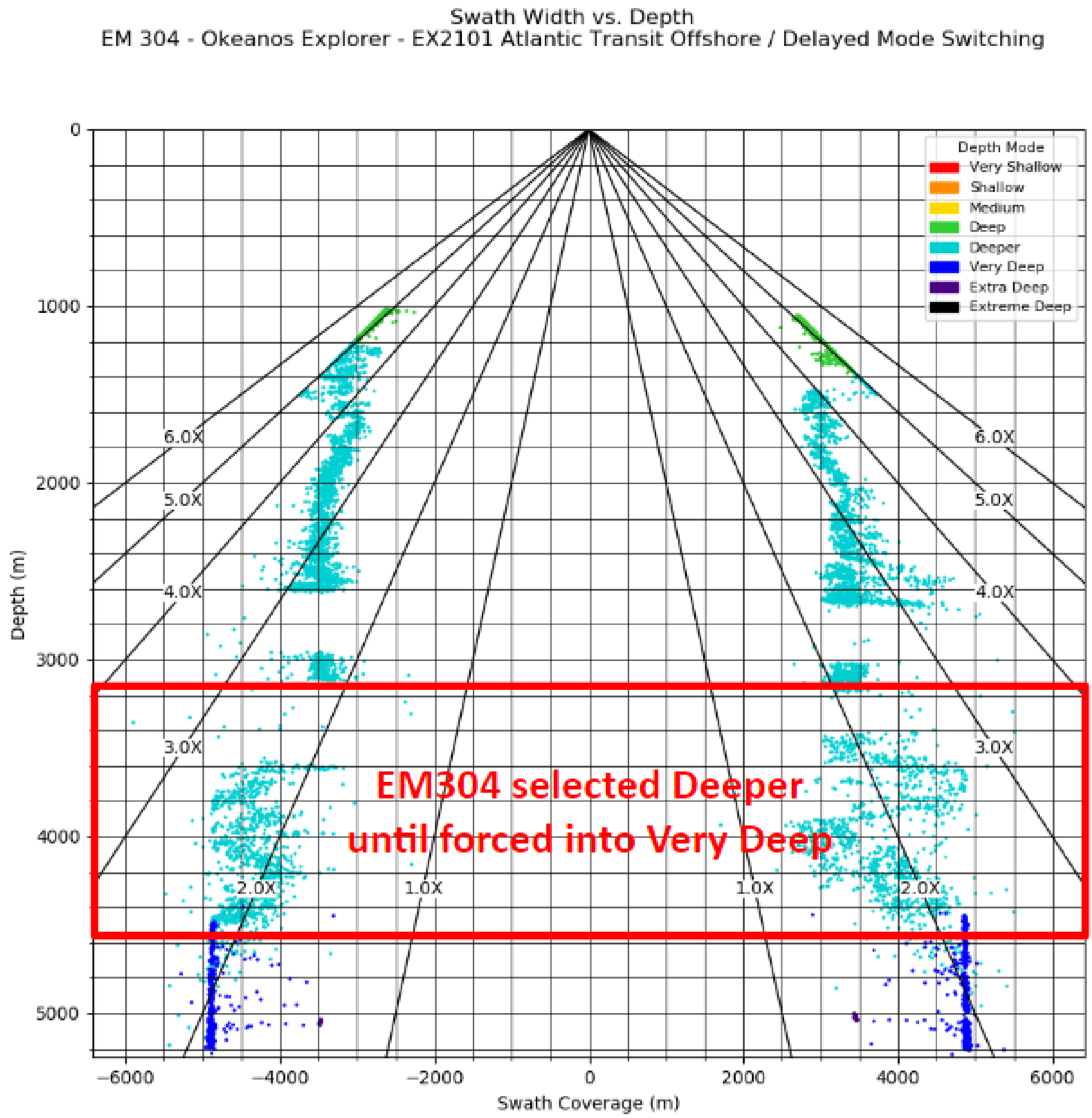

Figure 4. Plot of EM 304 swath width as a function of depth (in meters) while the depth mode remained in Deeper beyond the intended range.

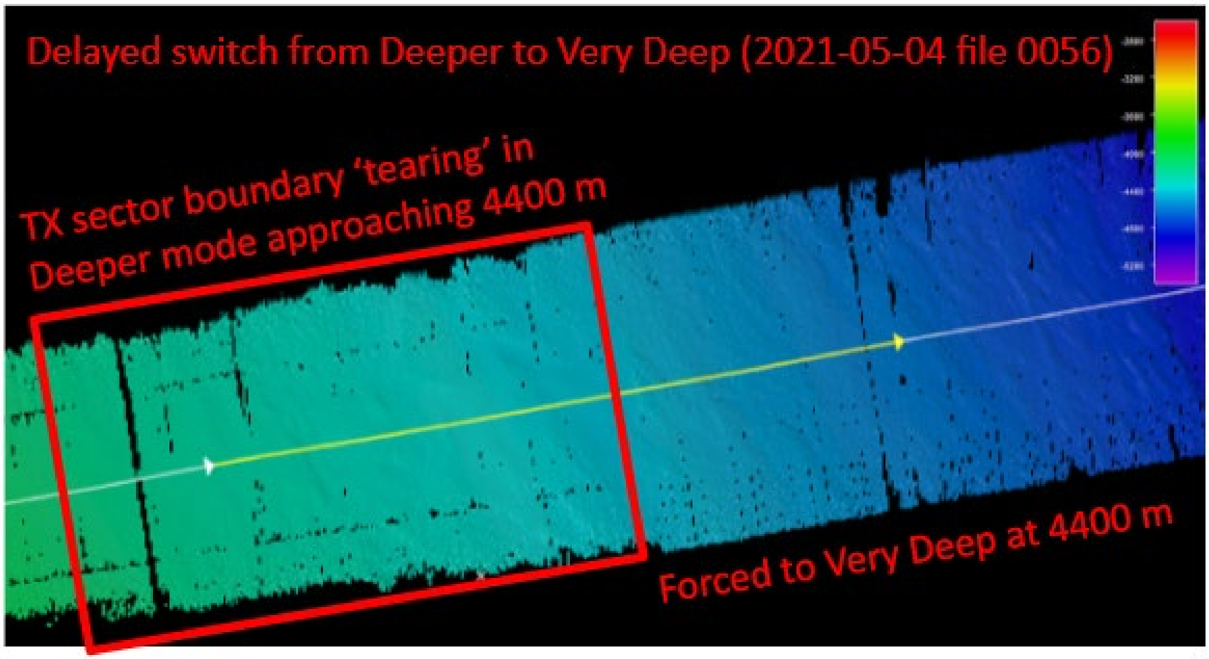

Figure 5. Example of sector boundary tearing seen in data collected in Deeper mode in depths approaching 4,400 m (depths in meters).

During the return transit from the 5,200 m reference site the depth modes were manually selected based on the expected transition depths from the EM 304 specifications (**Figure 6**). The ship was heading directly into the swell with high winds, causing bubble sweep and reducing the swath width in comparison with the typical expected coverage.

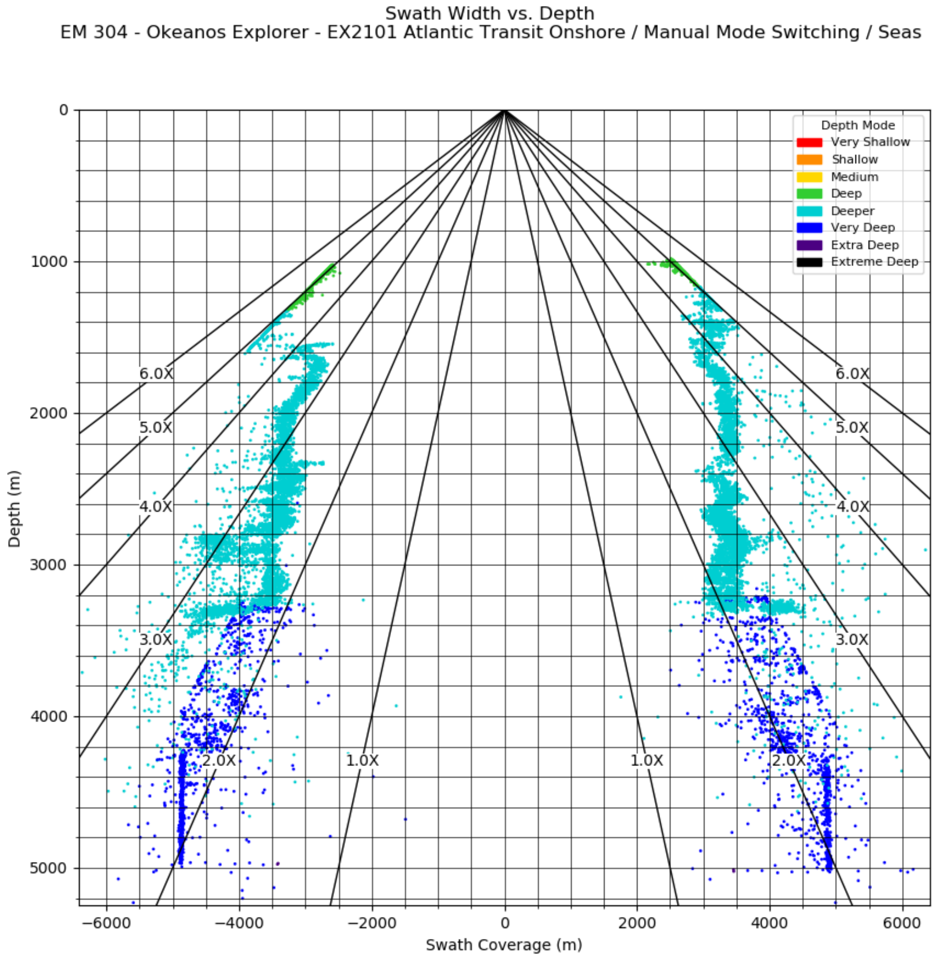

Figure 6. Plot of EM 304 swath width as a function of depth (in meters) while the depth modes were manually selected.

Coverage from both transits likely supports a Deeper to Very Deep transition depth of 3,500 m. This is a compromise between coverage (possibly greater in Deeper mode as Very Deep is limited to coverage angles of ±52°), swath quality (improved with full FM over CW/FM in Deeper mode), and sounding density (dual swath in Deeper, single swath in Very Deep).

In **Figure 7** the EX-21-01 EM 304 MKII data (colored by depth) are plotted over EX-19-02 and EX-18-10 data (gray). The maximum swath angles were reduced from ±75° in the EM 302 to ±70° in the EM 304, reducing the total coverage in shallow depth ranges where attenuation is not yet limiting (shallower than 1,000 m). Between 1,000 and 1,500 m the EM 304 MKII generally maintained near-maximum swath angles, coinciding with the start of the EM 302 coverage roll off where attenuation begins to limit coverage.

Between 1,500 and 3,500 m the EM 304 MKII achieved 0.25 to 1.0 times the water depth of additional coverage beyond the EM 302 curve.

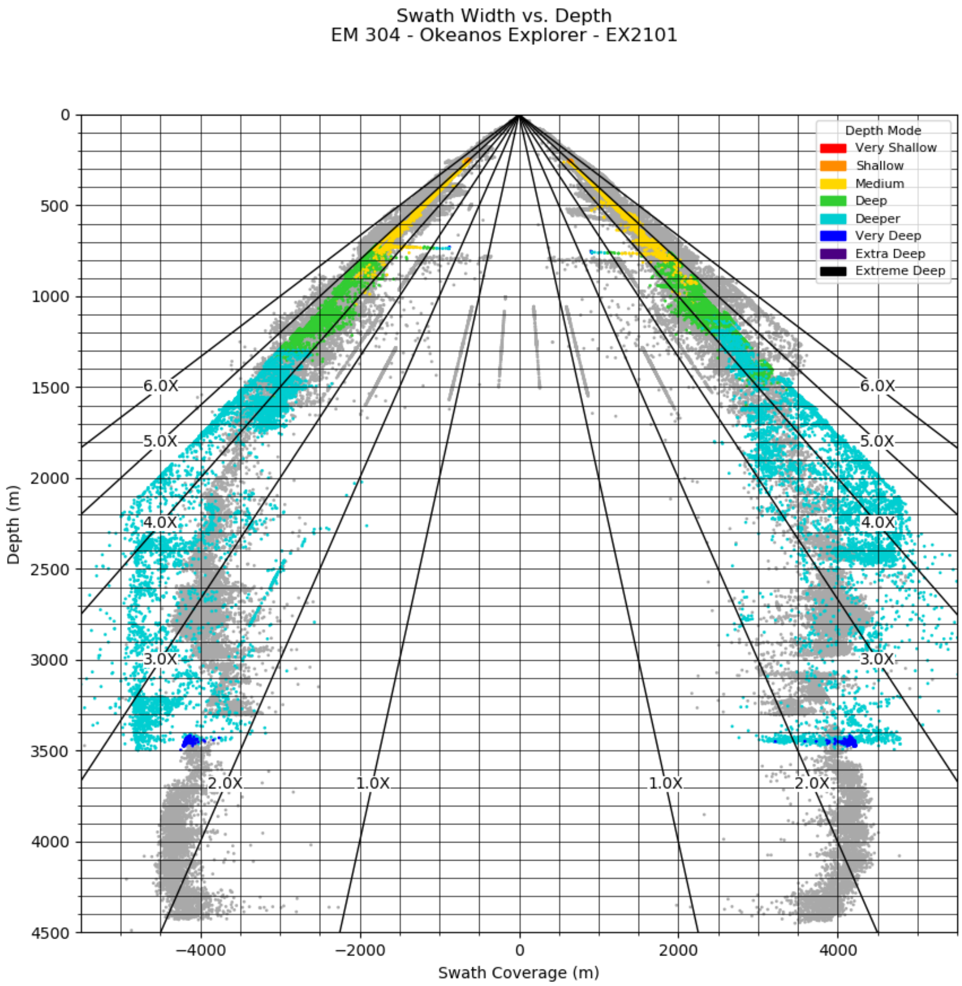

Figure 7. Plot of EX-21-01 EM 304 extinction testing data (colored by depth) over EX-19-02 and EX-18-10 EM 302 data (in gray).

EX-21-01 data generally show a downward shift in mode transition depths, such as the increase in the transition from Deeper (CW/FM) to Very Deep (FM) mode to approximately 3,400 m in this data set. Historically this transition from a mixed CW/FM to full FM occurred near 3,000 m where coverage fell below ±52°, which is the max swath angle in Very Deep mode. The EM 304 MKII achieves broader coverage in this depth range by maintaining Deeper mode to approximately 3,400 m. **Figure 8** shows a plot of the depth mode utilized at depth.

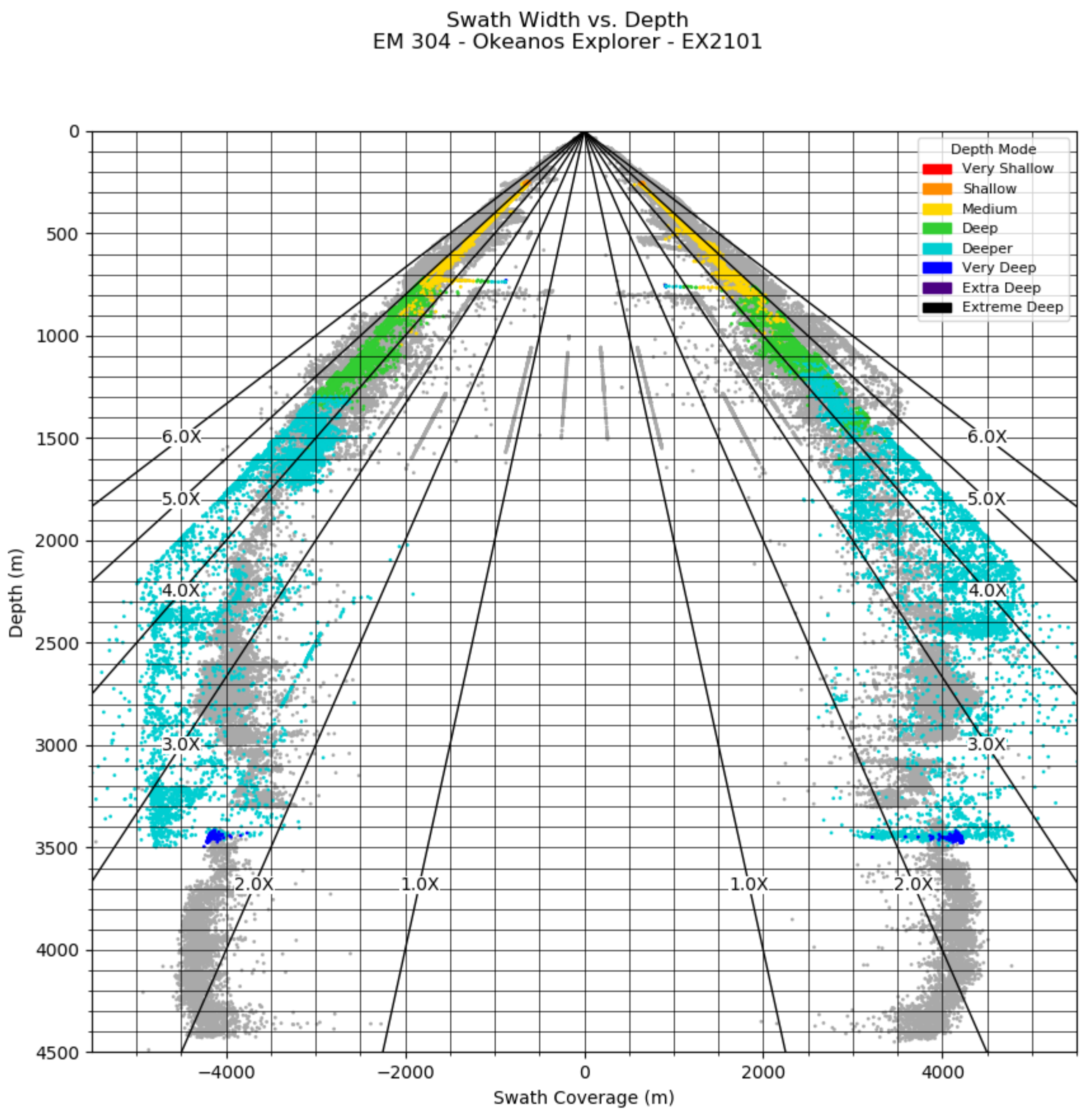

Figure 8. Plot of EX-21-01 EM 304 extinction testing colored by depth mode.

Data Rates

The EX-21-01 swath coverage data described above were used to assess the data rates versus depth with the latest .kmall format under typical mapping configurations. Rates were estimated by tracking bytes and time between ping datagrams, and extrapolating to hourly rates in a 100 ping moving average. Water column rates were estimated by scaling the bathymetry data rates by a factor of .kmwcd/.kmall size for each file. These examples include a single attitude source and do not include water column phase data or extra detections. **Figure 9** shows a plot of the data rates of just the .kmall and the .kmall plus .kmwcd files (colored by mode), and EX-19-02 EM 302.all and .all plus .wcd files (black) versus depth.

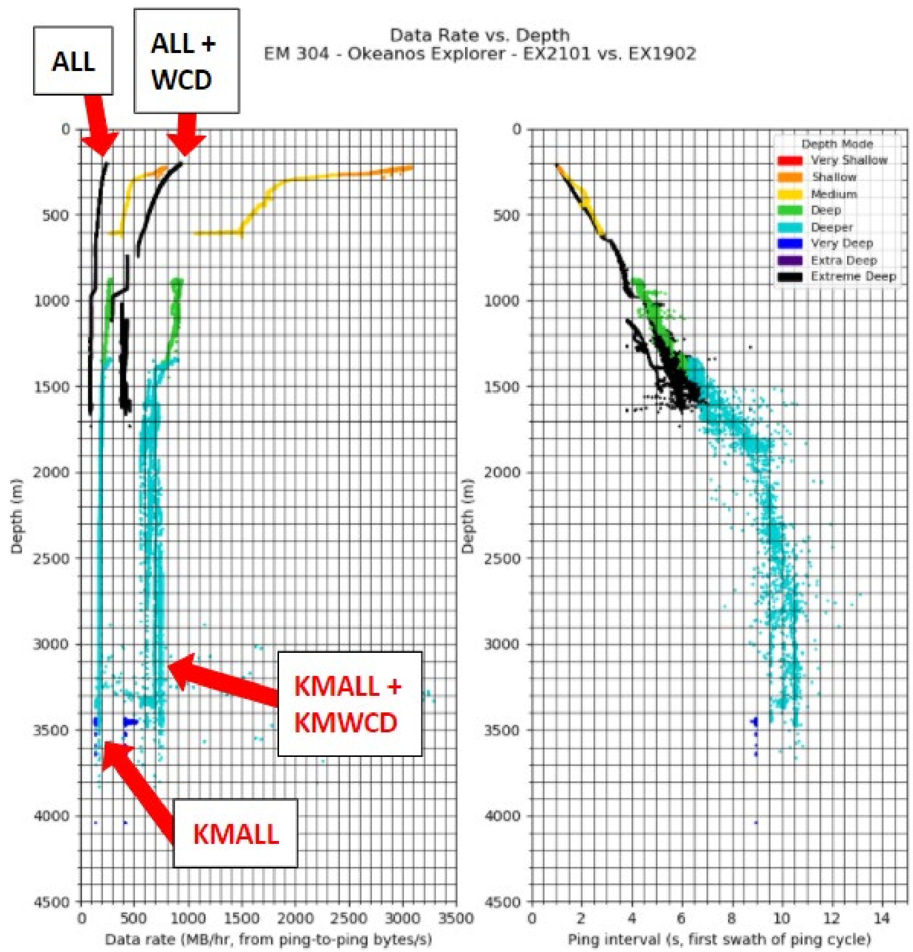

Figure 9. Plot of EX-21-01 (colored by depth) and EX-19-02 (black) data rates (left) and ping interval (right) versus depth in meters.

RX Noise Built-in Self Tests Assessment

Major limitations of multibeam performance can stem from elevated noise levels due to hull design, engines and machinery, sea state, biofouling, electrical interference, etc. To characterize the vessel's noise environment as perceived by the EM 304, a series of "continuous" RX noise level BISTs were recorded while slowly accelerating and decelerating from 0-165 rpm. These speeds correspond to approximately 1-10 knots over ground, or 2-11 knots. **Figure 10** shows EM 304 RX noise level versus speed in relatively calm seas (2-4 swell, winds less than 10 knots). The vertical stripes are likely caused by swell impacting the hull during the RX noise test cycle, illustrating the broadband noise perceived in elevated sea state and are not representative of typical machinery or flow noise.

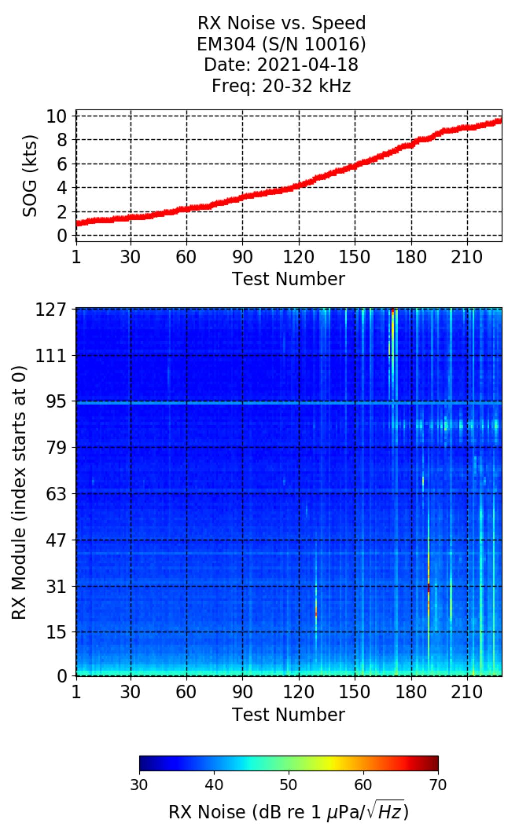

Figure 10. EM 304 RX noise level versus speed.

The EM 304 MKII upgrade involved only TX hardware, and therefore the RX hardware has not changed since the EX-20-00 EM 304 SAT. The 2021 RX noise data set covers a broader frequency band, with the MKII TX upgrade shifting the range to 20-32 kHz from the 26-34 kHz of the MKI.

EX-21-01 results show very small changes in noise levels with speeds up to 7 knots, indicating low flow and machinery noise in this range. This is in line with the EX-20-00 SAT results. A small increase was noted in the low-speed noise floor compared to EX-20-00, reflecting a possible increase in ship noise and/or greater susceptibility to similar ship noise in the lower MKII band. Noise levels begin to increase appreciably at speeds above 8 knots, though the increase is not as drastic as observed in previous years.

Importantly for SAT considerations, the combination of the new EM 304 transceiver (2020) and the changes in filtering related to the MKII upgrade (2021) appear to have eliminated most of the consistently high noise levels for specific modules. These were seen as horizontal striping across all tests of the EM 302 (2019) and the EM 304 MKI (2020) (**Figure 11**).

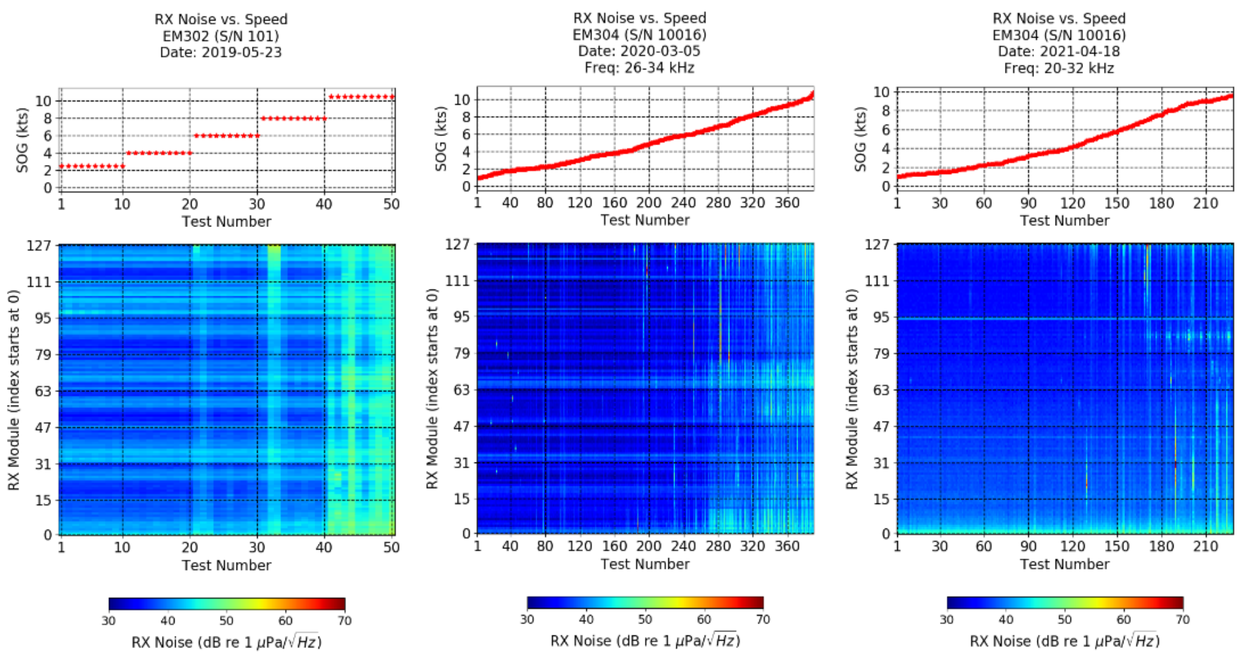

Figure 11. Comparison of previous speed noise tests conducted with the EM 302, EM 304 MKI, and EM304 MKII.

TX Channels BIST Assessment

Though TX impedance trends can be monitored through TX Channel BISTs which provide a useful proxy for array impedance that will generally indicate if an element has shorted or failed, they are not a replacement for direct measurements, such as the Cypher reports which include more detailed electrical properties for each element.

TX channels BIST data collected dockside in Key West, Florida on April 16, 2021 are shown in **Figure 12**. These BISTs indicate normal impedance levels for all but two channels at the start of the MKII TX array service life.

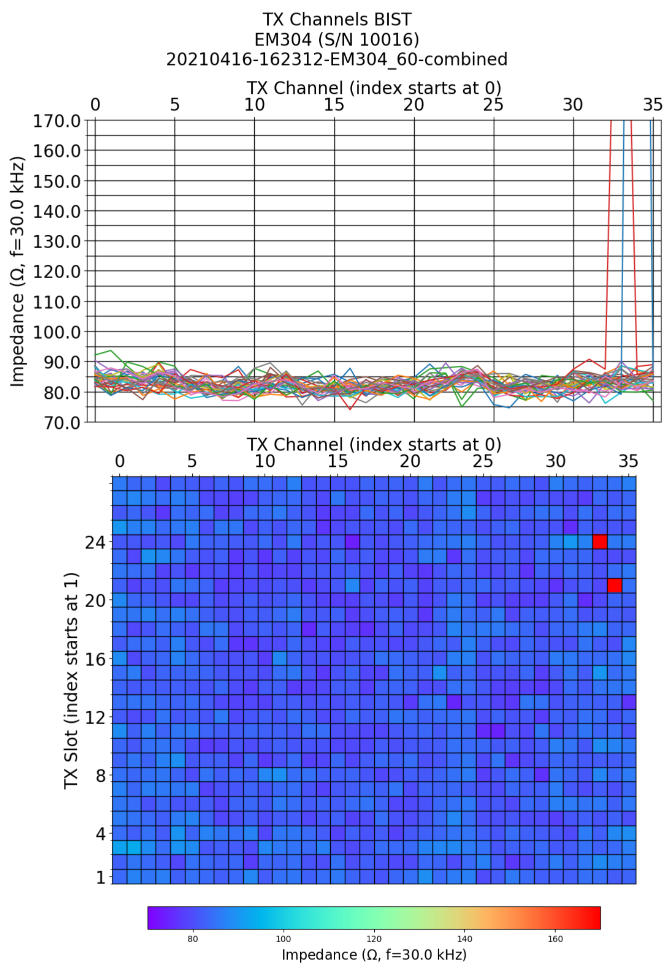

Figure 12. EM 304 TX BIST data collected during EX-21-01.

A significant difference between EM 304 MKI and EM 304 MKII is the number of TX slots (48 for the MKI and 28 for the MKII). All but two elements in the new MKII TX array fall within specifications, representing the TX impedance baseline at the start of MKII service life.

Accuracy Testing

Accuracy, in the sense of self consistency, of a multibeam echosounder under "normal" survey conditions can be assessed by examining soundings collected during single-pass survey lines over a trusted bathymetric surface (a reference surface). Reference surfaces typically cover flat or gently sloping terrain that have been carefully and densely surveyed, providing a large sample count and high degree of confidence in the depth of each grid cell.

Accuracy assessments provide a baseline for each mode and can help to reveal changes to the system (e.g., reduced accuracy due to low transmit power from a degraded array) as well as changes to the operation environment (e.g., impacts of noise on the distribution of soundings and achievable swath width). With consistent analysis methods, accuracy performance data can provide a critical window into performance over the system's service life and may help to identify early signs of component failure.

Testing Procedure

During EX-21-01, EM 304 MKII accuracy was assessed using reference surfaces and crosslines at depths of 250, 1,100, 3,400 (**Figure 13**), and 5,200 m (**Figure 14**). These depths were selected to assess accuracy in different modes that may be automatically selected by the system in similar terrain.

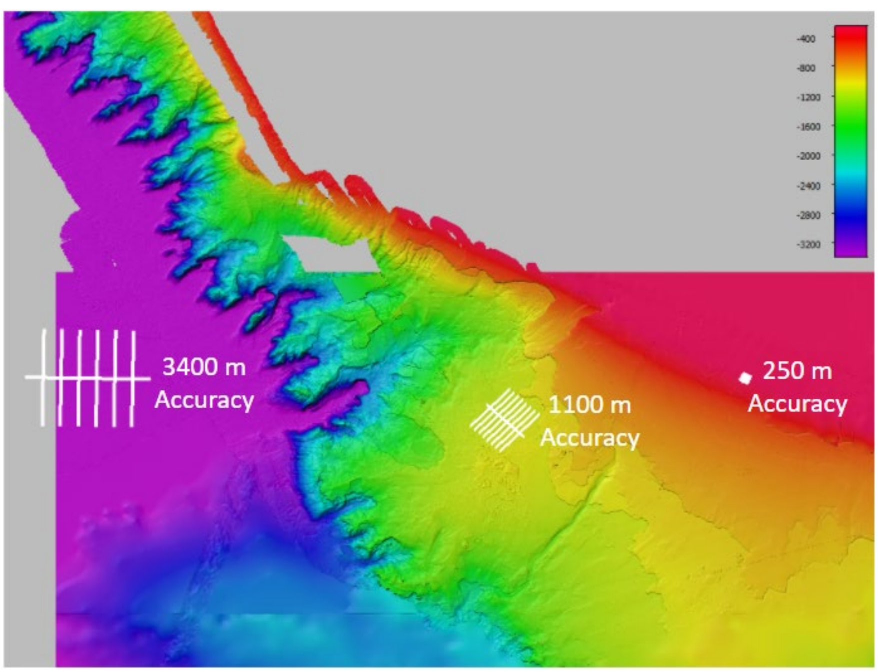

Figure 13. Overview of 250, 1,100, and 3,400 m accuracy testing conducted during EX-21-01 (depths in meters).

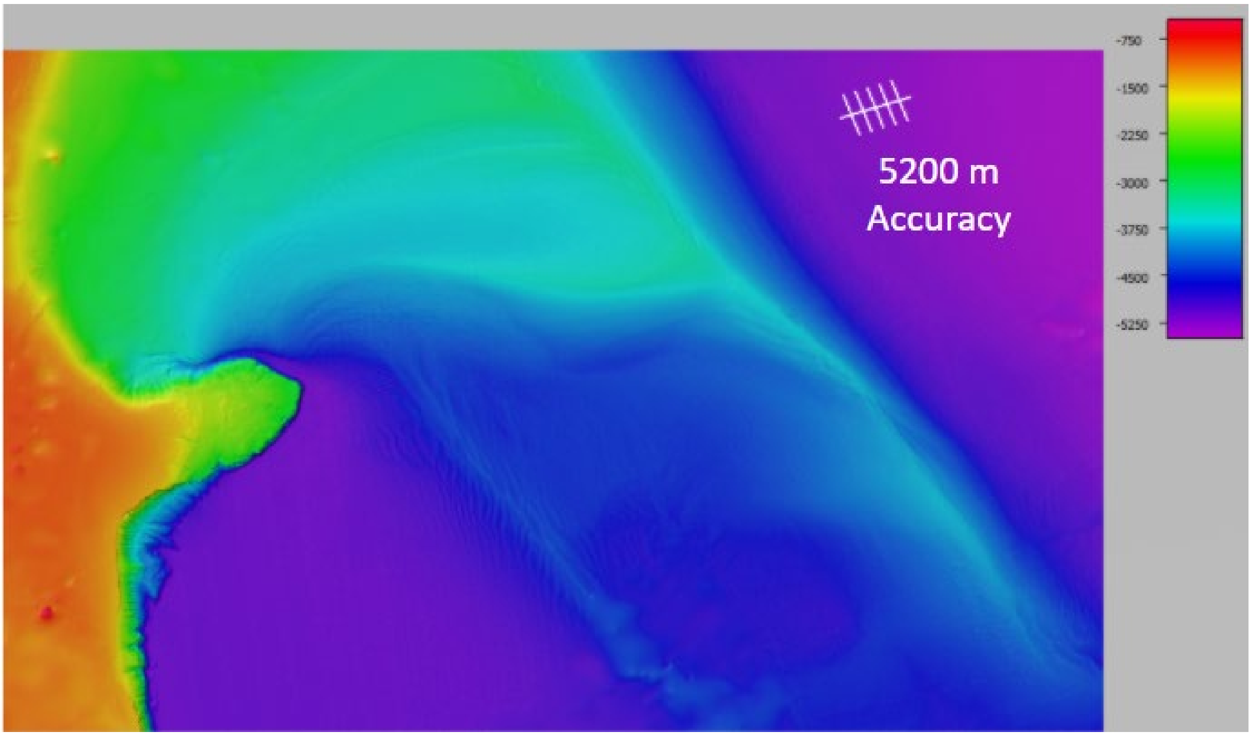

Figure 14. Overview of 5,200 m accuracy testing conducted during EX-21-01 (depths in meters).

Swath accuracy was assessed for each mode by conducting a dense reference survey in the mode that would be automatically selected for the depth, and then running a series of crosslines over the generated surface in suitable modes for that depth range. Crosslines were oriented orthogonally to the reference surface in order to reduce any potential coupling of echosounder biases across the swath.

Sound speed profiles were collected throughout the surveys and crosslines and applied during data collection and processing. All reference survey lines were run at 6-7 knots, and the crosslines were run at 8 knots. A tide model (TPX09) was applied during post-processing for the 250 m crosslines, with amplitudes on the order of 0.2 m. No tidal data were applied to the deeper test data, as the amplitudes are insignificant in these depths.

The reference surfaces were gridded with the CUBE algorithm in QPS Qimera at appropriate resolutions, and then filtered by slope, sounding density, and uncertainty in the NOAA/MAC accuracy plotter application. Only reference surface cells meeting the slope, density, and uncertainty criteria were used for analyses of crossline data.

Crossline soundings were filtered to remove outliers based on distance from the reference grid, excluding soundings that are not representative of the normal swath behavior and would readily be flagged during routing processing. Other systemic behavior of the echosounder was not edited or impacted.

Sounding depths were compared to reference grid depths, and mean depth bias and depth bias standard deviations as a percentage of water depth were then computed in 1° angular bins across the swath for each configuration.

Results Overview

The EM 304 provided expected performance across all depth modes, with generally zero-mean biases across the swath and typical increases in the sounding difference standard deviations with increasing beam angle. The trends in standard deviations generally remain within the expected ranges after excluding soundings based on a depth-appropriate distance from the reference surface. Testing indicated an improvement in the horizontal and vertical sounding distributions with yaw stabilization enabled to relative mean heading. See **Appendix 1** for plots of the accuracy testing results for each mode in each depth.

In some cases, very small roll biases may be apparent in the mean depth trend lines. Roll verification results using crosslines at the 3,400 m and 1,100 m sites were centered around zero. No further roll adjustments have been made.

The MKII showed an improvement in nadir tracking with the penetration filter set to both Weak and Off. This may also stem from a depth gate filtering around the reference depth. The crosslines suggest that the “Erik’s Horns” or “railroad track” effect near nadir may be reduced if this filter can be disabled. It should still be applied in depths and seafloor types where the system is persistently mistracking at nadir.

Backscatter Normalization

Backscatter normalization data were collected at two sites with relatively flat, uniform seafloor characteristics that were used previously by *Fugro Brasilis* as a means to establish a reference area for vessels working in the region. Normalization lines were surveyed at 5 knots to reduce noise levels and increase alongtrack sounding density.

Site 1 in **Figure 15** (approximately 1,000 m depth) was used for Shallow, Medium, and Deep modes. Sea state deteriorated during the tests leading to frequent bubble sweep along the arrays, resulting in potential backscatter “blowouts” that may present difficulties in processing.

Site 2 in **Figure 15** (approximately 3,000 m depth) was used for Deep, Deeper, and Very Deep modes. The use of Deep mode at both sites tied them together.

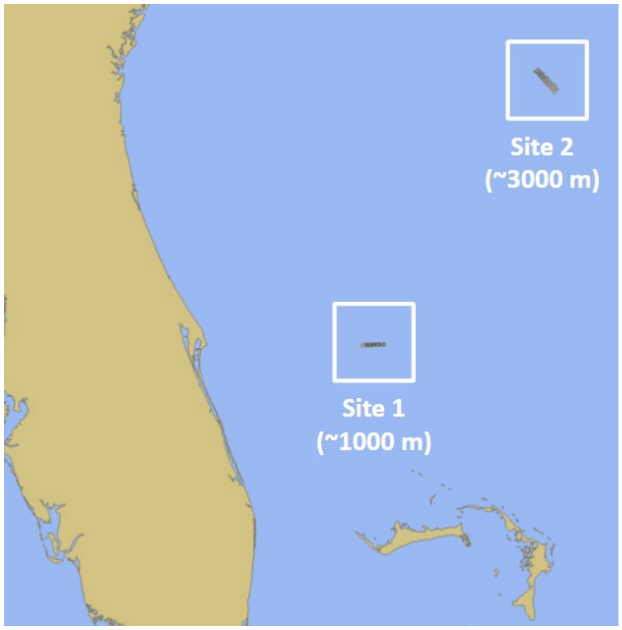

Figure 15. Overview of the sites used for backscatter normalization.

The example backscatter mosaics from processed GSF files in QPS FMGT are shown for overview purposes only in **Figure 16**. The normalization data package will be processed by Kongsberg to establish backscatter correction settings with the new EM 304 topside unit (2020) and MKII TX array (2021). When available, the results will be updated in SIS settings and a note will be added to the EX-21-01 archived data on how to back-apply settings.

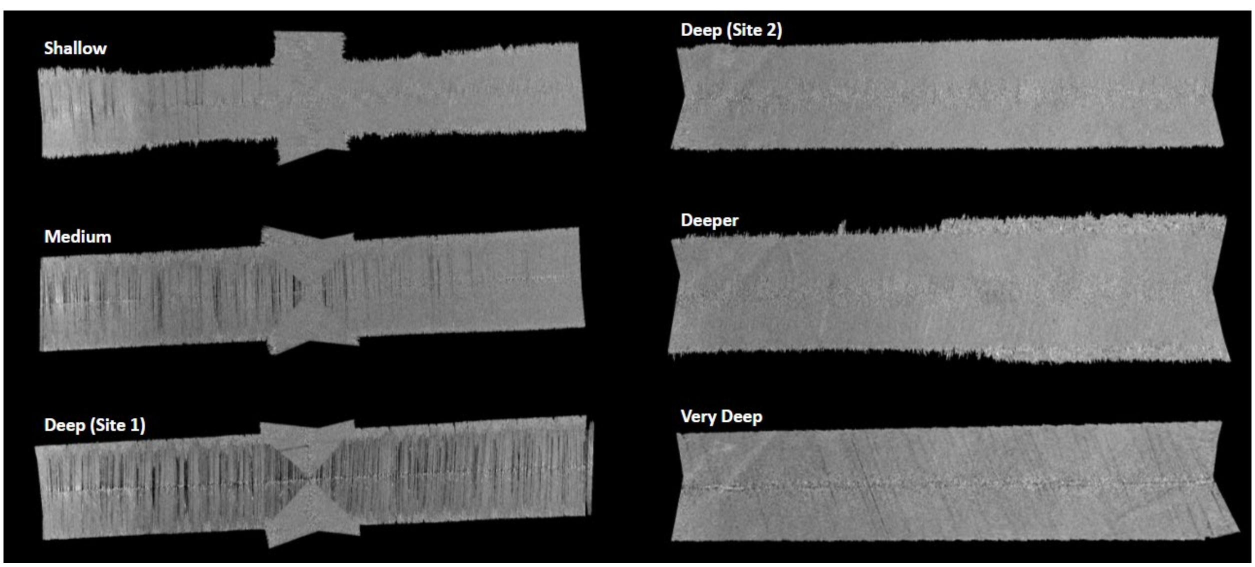

Figure 16. Example backscatter mosaics from data acquired at the backscatter

normalization sites.

Appendix 1: EM 304 Accuracy Testing Results

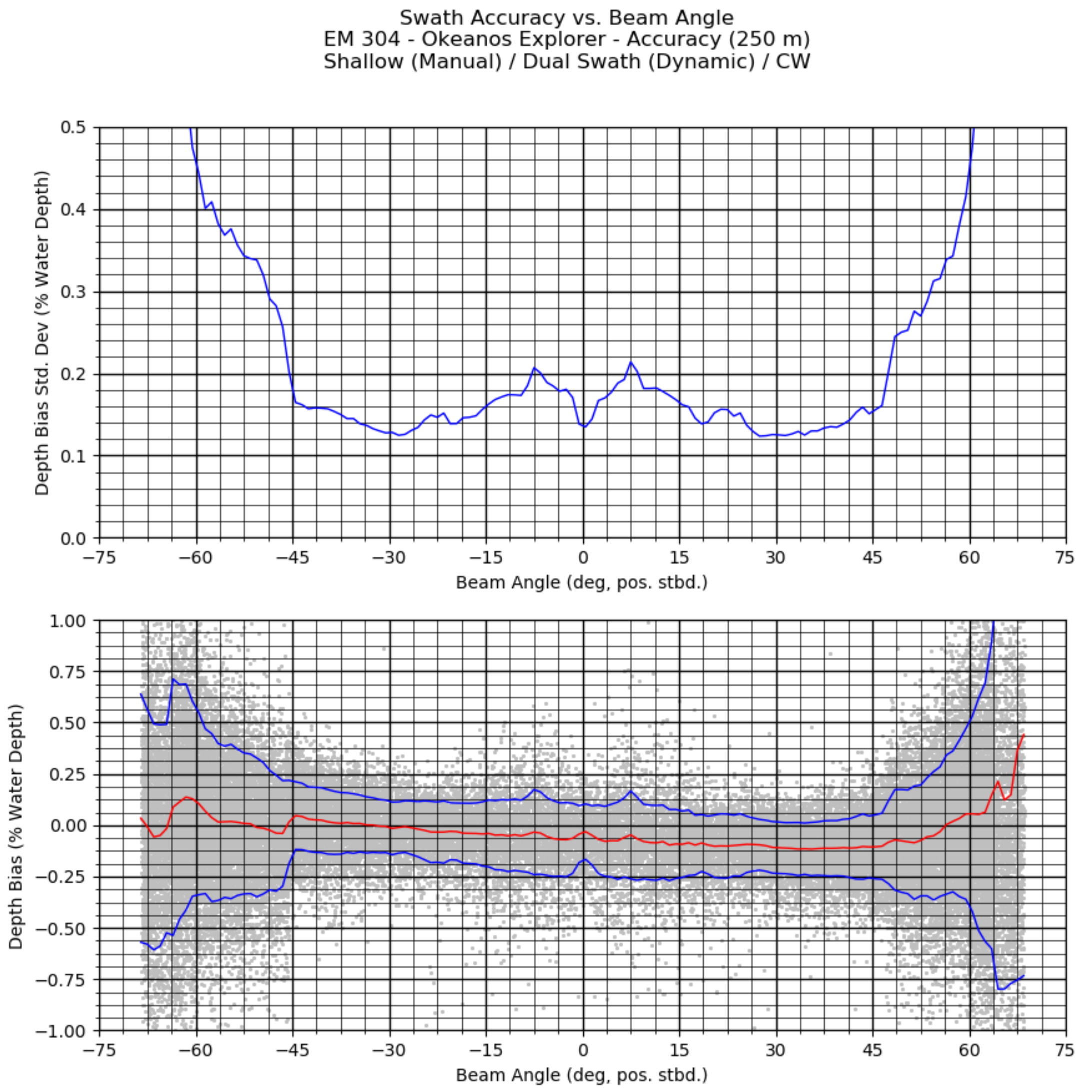

Figure A-1. Shallow mode crosslines over the 250 m reference surface, swath accuracy depth bias (bottom) and depth bias standard deviation (top) plotted against beam angle. Mean depth difference is plotted in red, and depth difference standard deviation is plotted in blue.

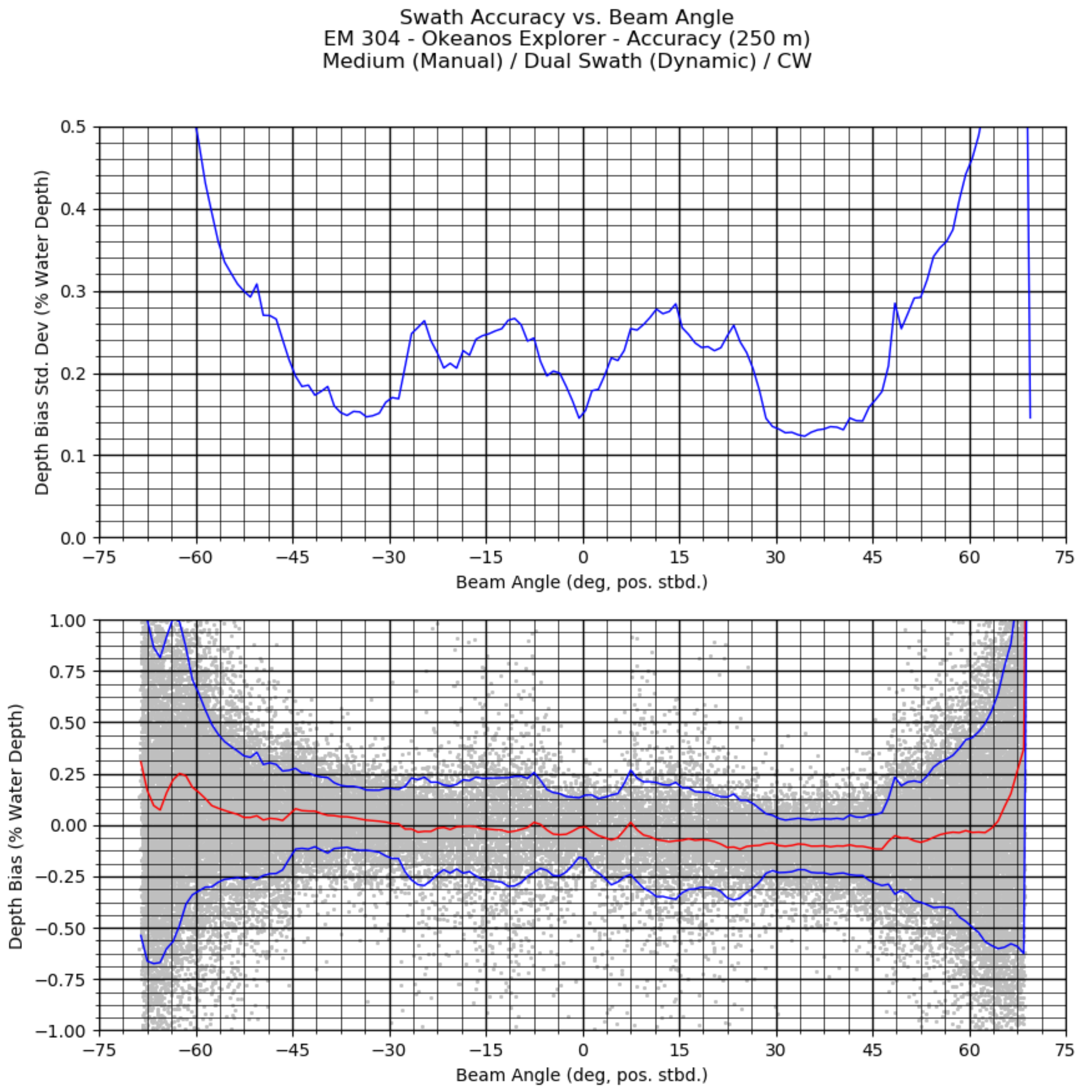

Figure A-2. Medium mode crosslines over the 250 m reference surface, swath accuracy depth bias (bottom) and depth bias standard deviation (top) plotted against beam angle. Mean depth difference is plotted in red, and depth difference standard deviation is plotted in blue.

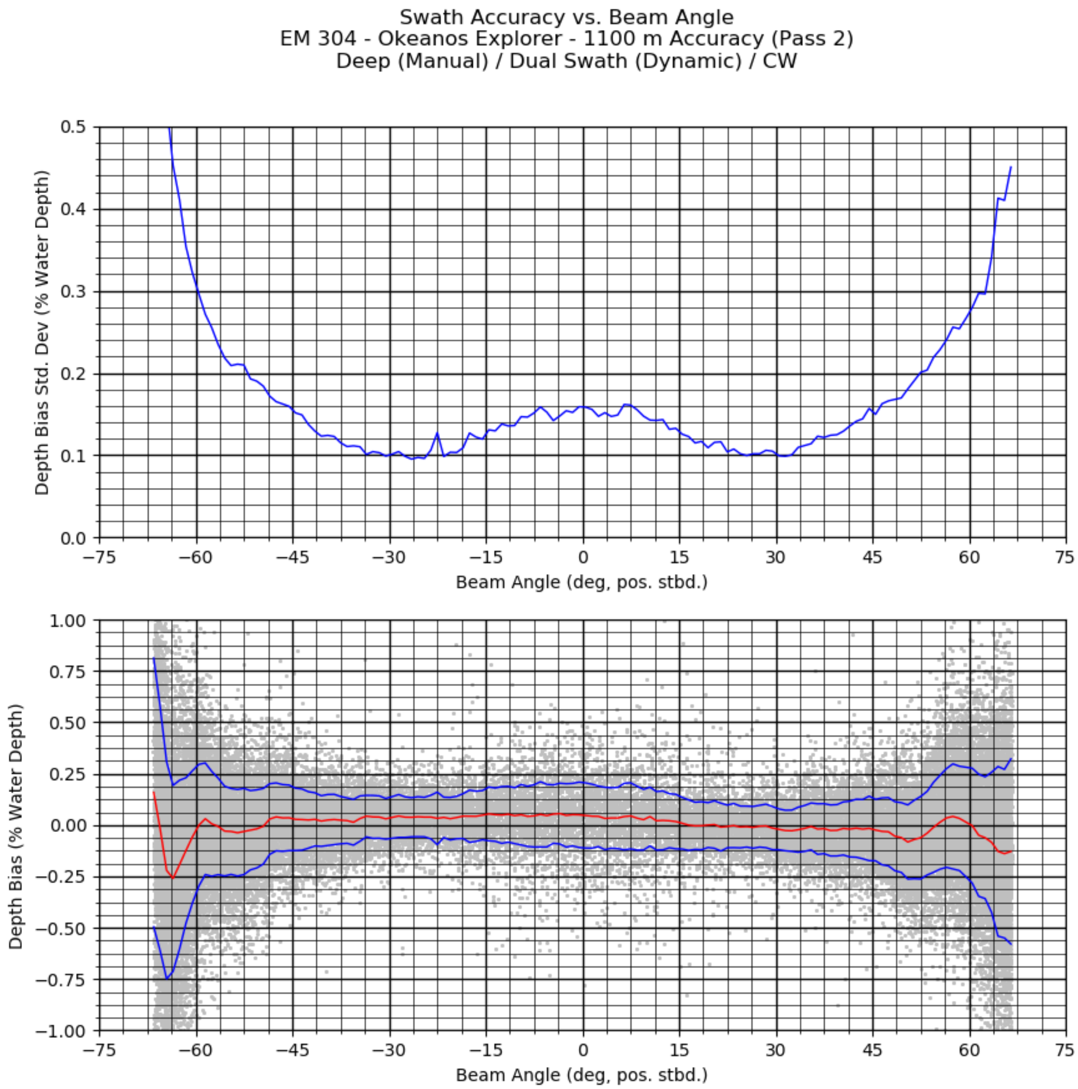

Figure A-3. Deep mode crosslines over the 1,100 m reference surface, swath accuracy depth bias (bottom) and depth bias standard deviation (top) plotted against beam angle. Mean depth difference is plotted in red, and depth difference standard deviation is plotted in blue.

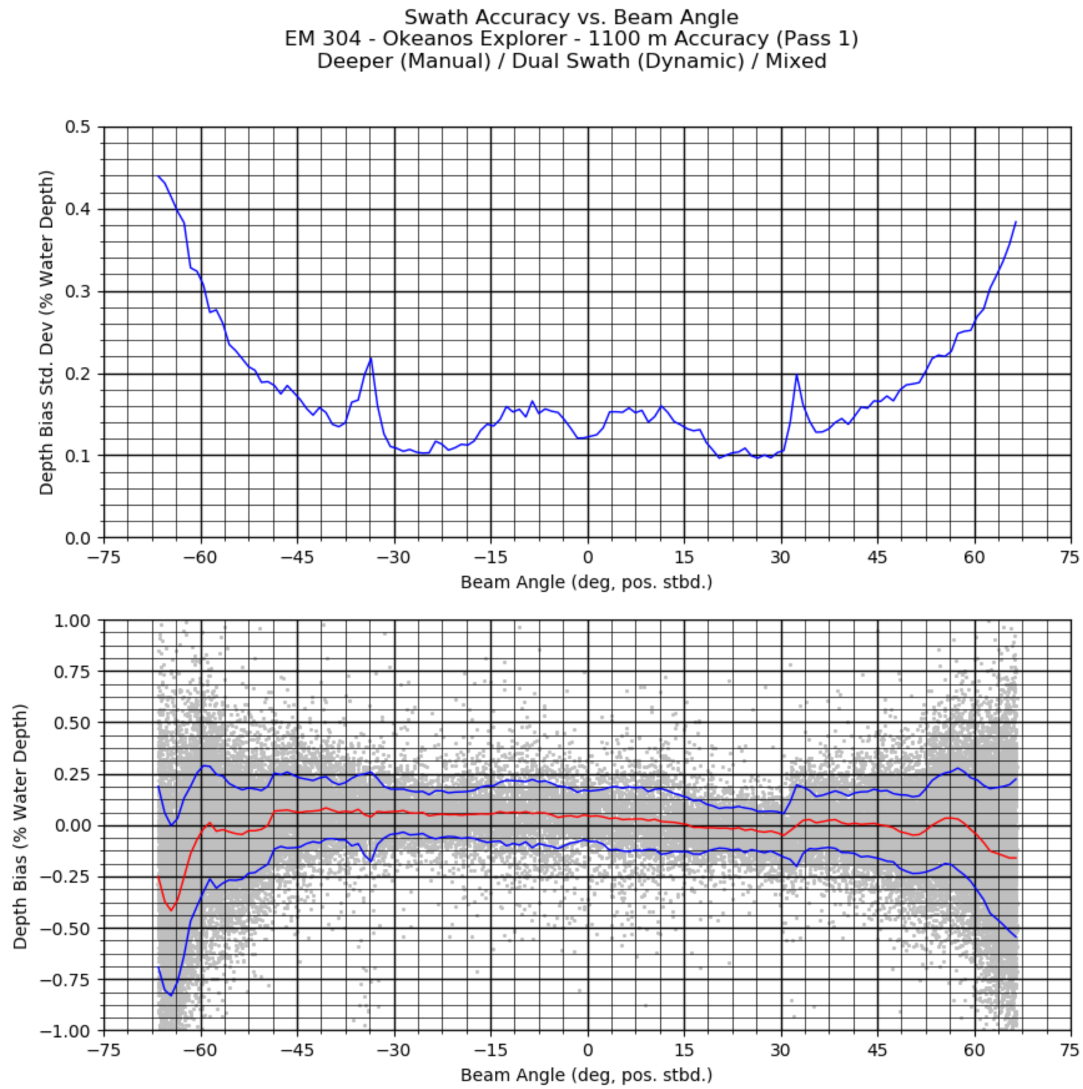

Figure A-4. Deeper mode crosslines over the 1,100 m reference surface, swath accuracy depth bias (bottom) and depth bias standard deviation (top) plotted against beam angle. Mean depth difference is plotted in red, and depth difference standard deviation is plotted in blue.

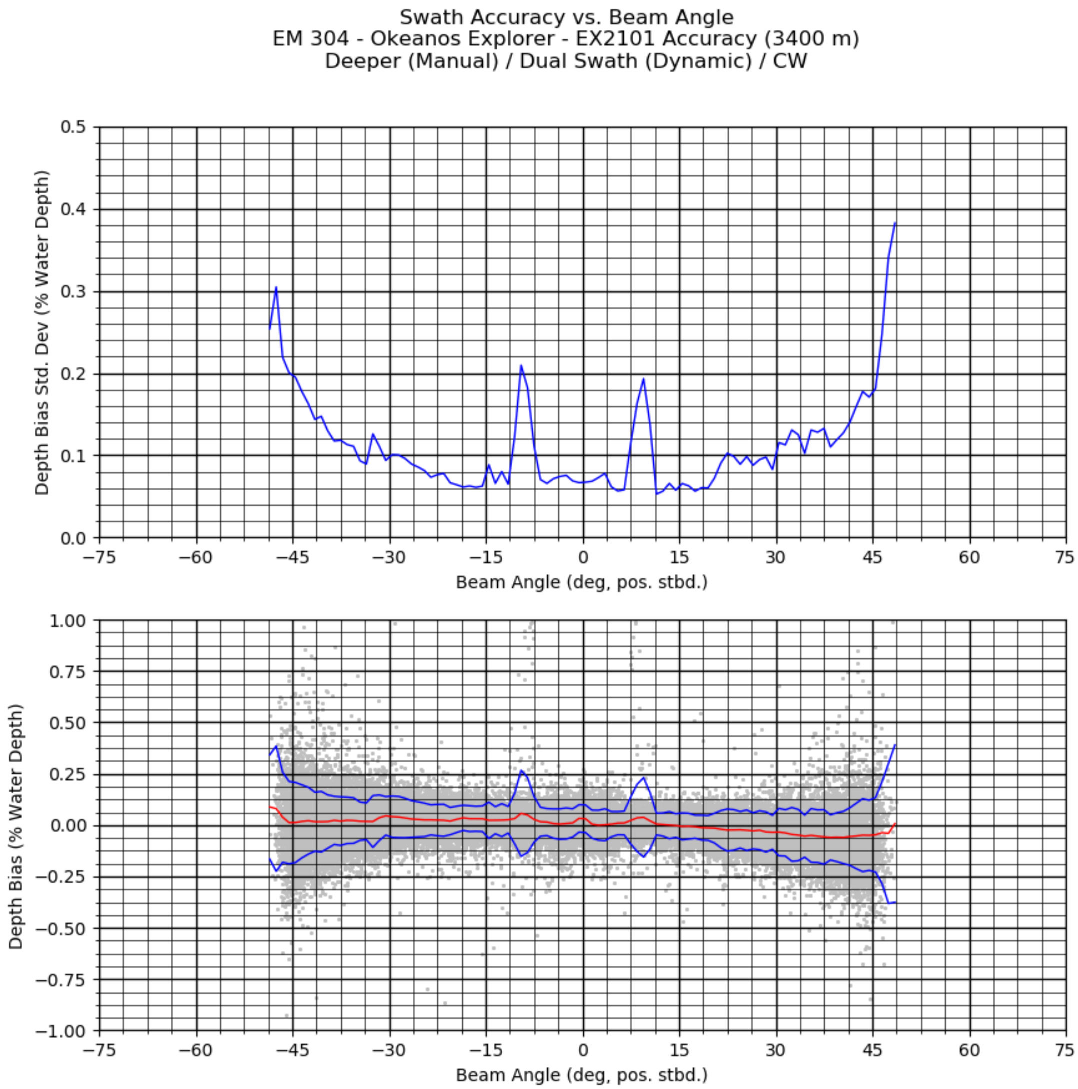

Figure A-5. Deeper mode crosslines over the 3,400 m reference surface, swath accuracy depth bias (bottom) and depth bias standard deviation (top) plotted against beam angle. Mean depth difference is plotted in red, and depth difference standard deviation is plotted in blue.

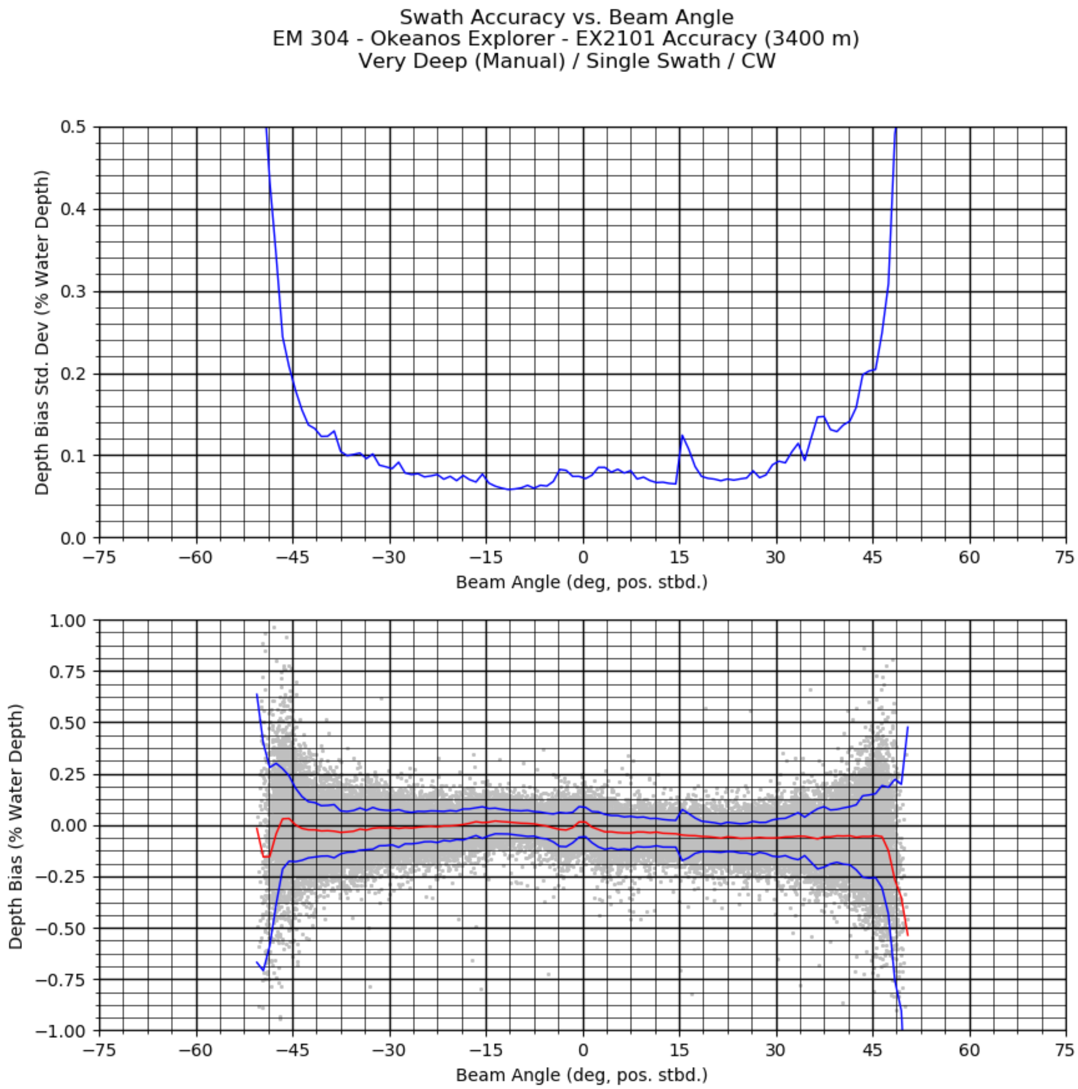

Figure A-6. Very Deep mode crosslines over the 3,400 m reference surface, swath accuracy depth bias (bottom) and depth bias standard deviation (top) plotted against beam angle. Mean depth difference is plotted in red, and depth difference standard deviation is plotted in blue.

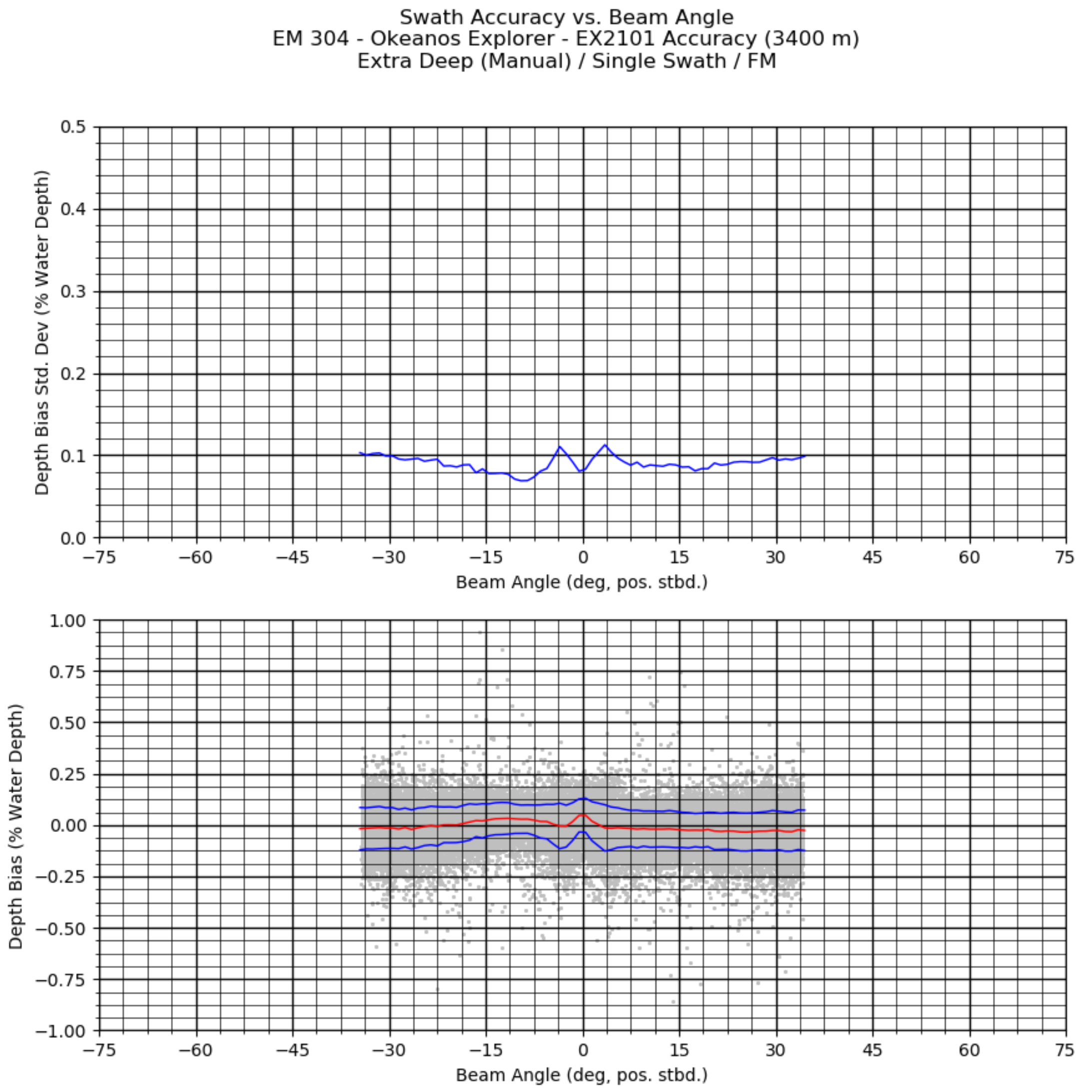

Figure A-7. Extra Deep mode crosslines over the 3,400 m reference surface, swath accuracy depth bias (bottom) and depth bias standard deviation (top) plotted against beam angle. Mean depth difference is plotted in red, and depth difference standard deviation is plotted in blue.

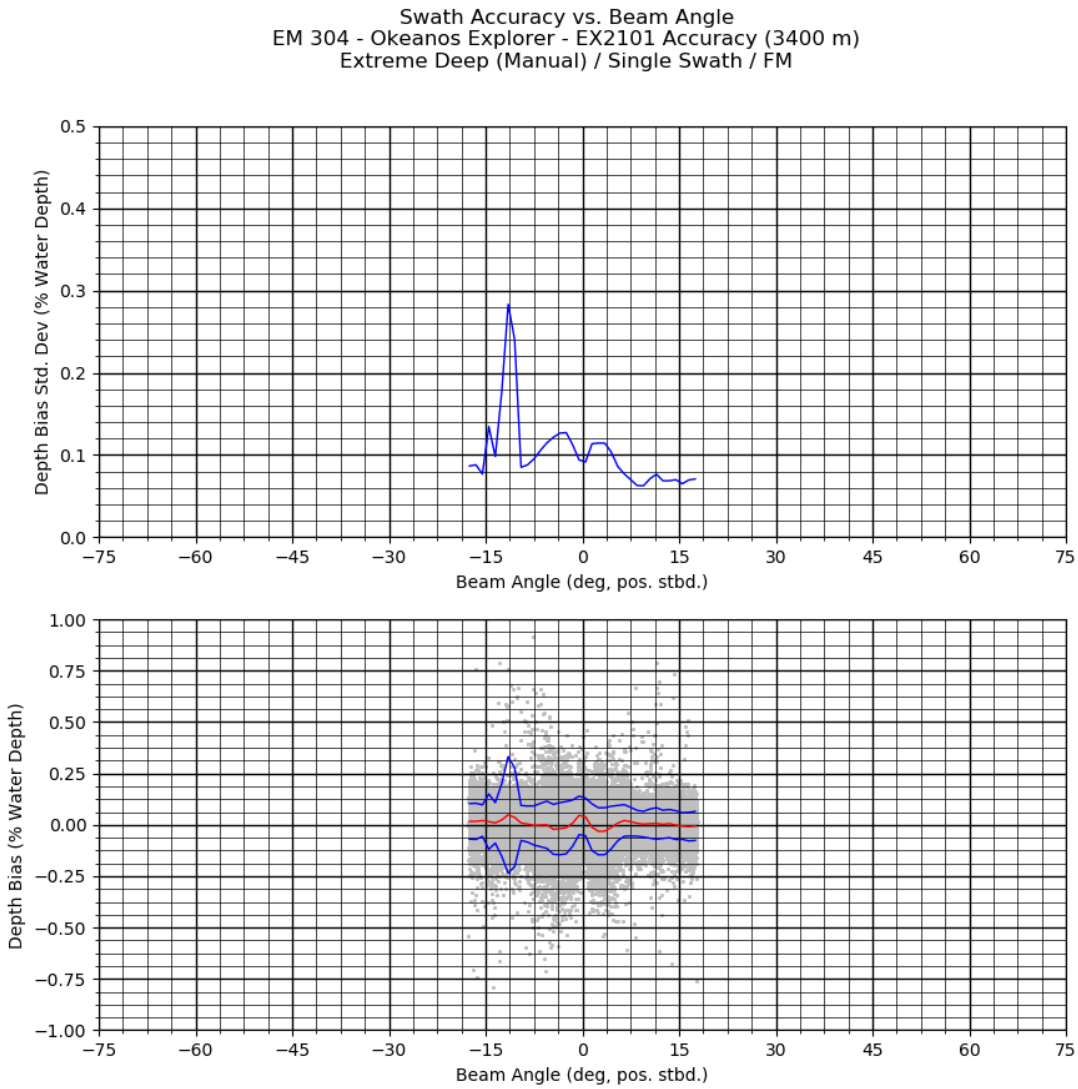

Figure A-8. Extreme Deep mode crosslines over the 3,400 m reference surface, swath accuracy depth bias (bottom) and depth bias standard deviation (top) plotted against beam angle. Mean depth difference is plotted in red, and depth difference standard deviation is plotted in blue.

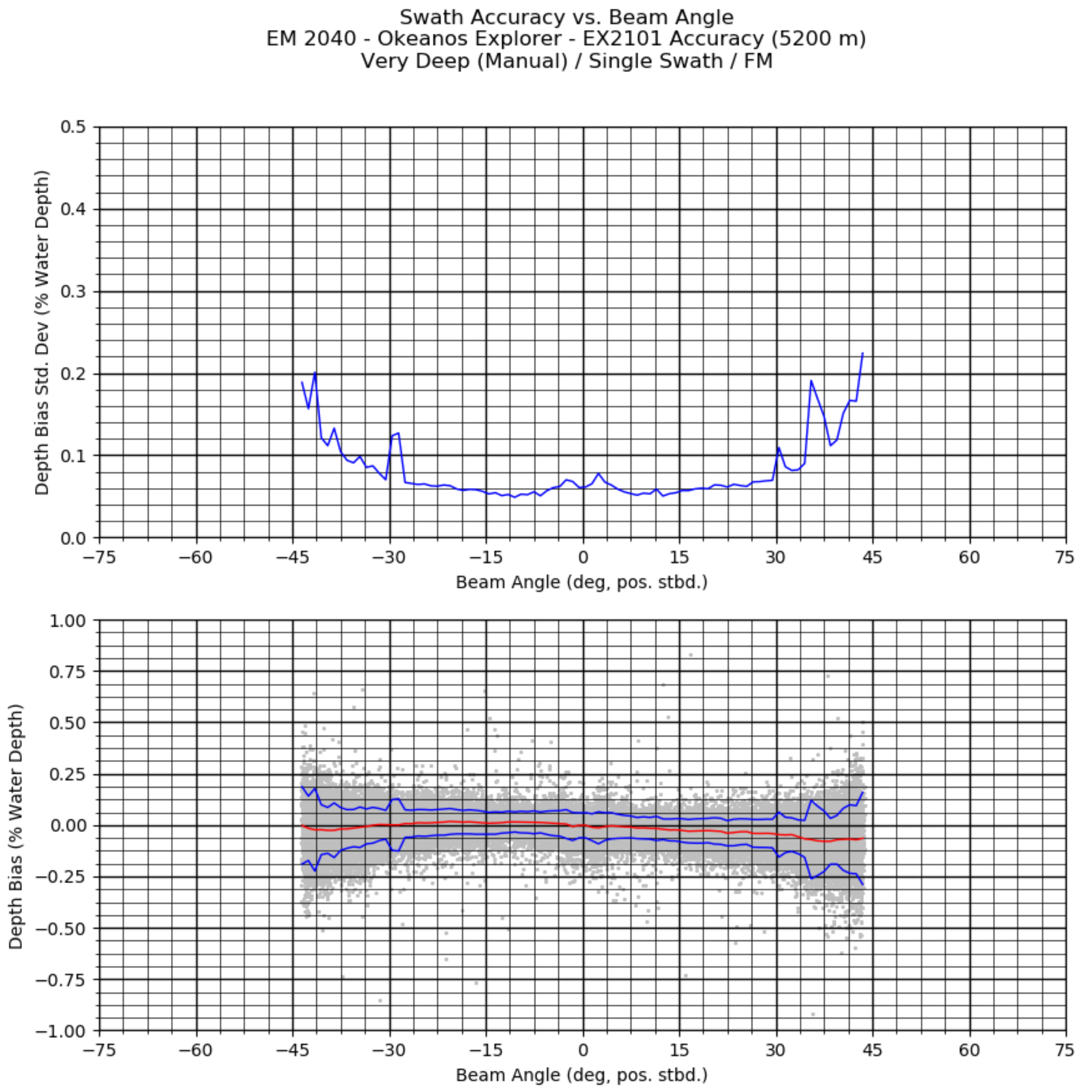

Figure A-9. Very Deep mode crosslines over the 5,200 m reference surface, swath accuracy depth bias (bottom) and depth bias standard deviation (top) plotted against beam angle. Mean depth difference is plotted in red, and depth difference standard deviation is plotted in blue.

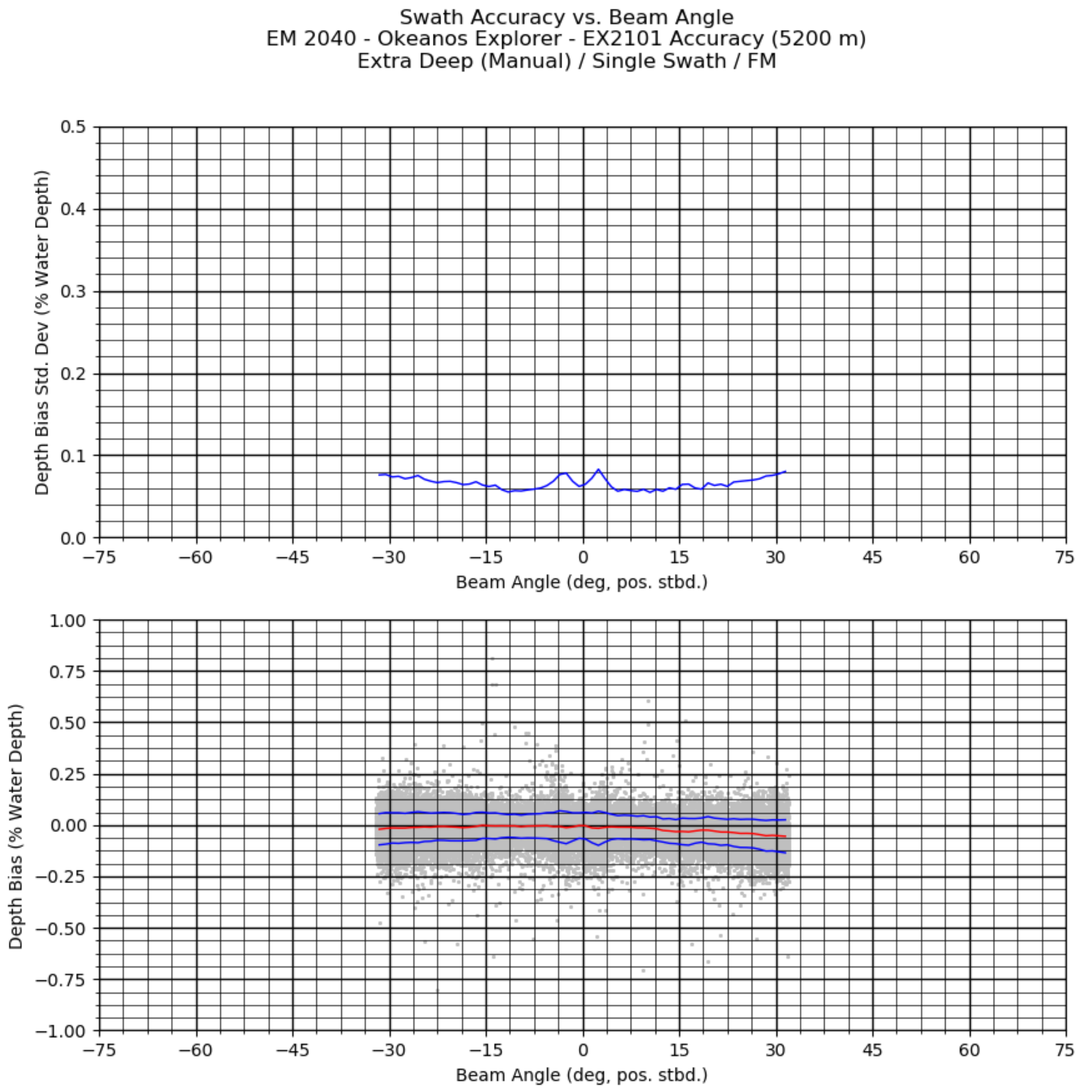

Figure A-10. Extra Deep mode crosslines over the 5,200 m reference surface, swath accuracy depth bias (bottom) and depth bias standard deviation (top) plotted against beam angle. Mean depth difference is plotted in red, and depth difference standard deviation is plotted in blue.

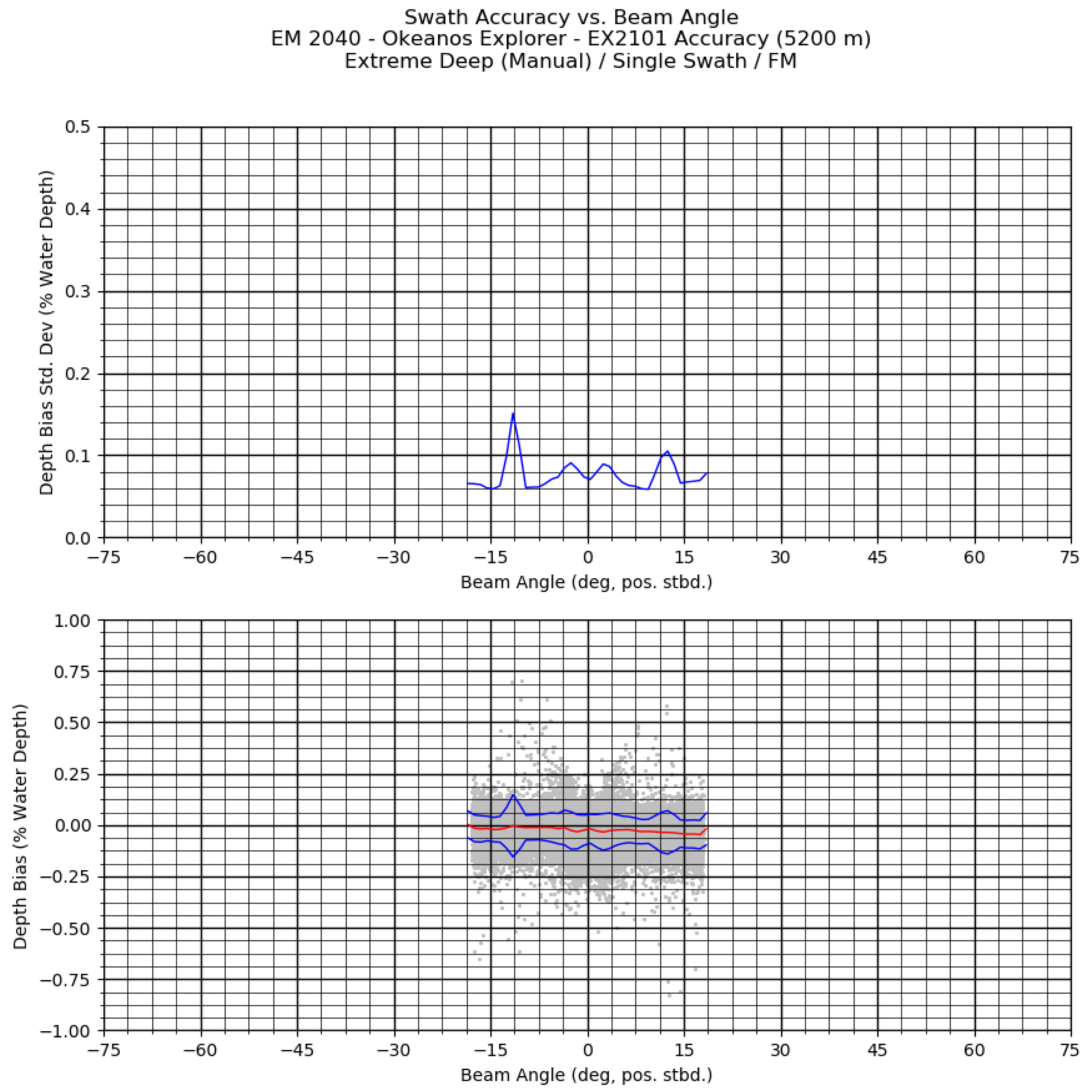

Figure A-11. Extreme Deep mode crosslines over the 5,200 m reference surface, swath accuracy depth bias (bottom) and depth bias standard deviation (top) plotted against beam angle. Mean depth difference is plotted in red, and depth difference standard deviation is plotted in blue.